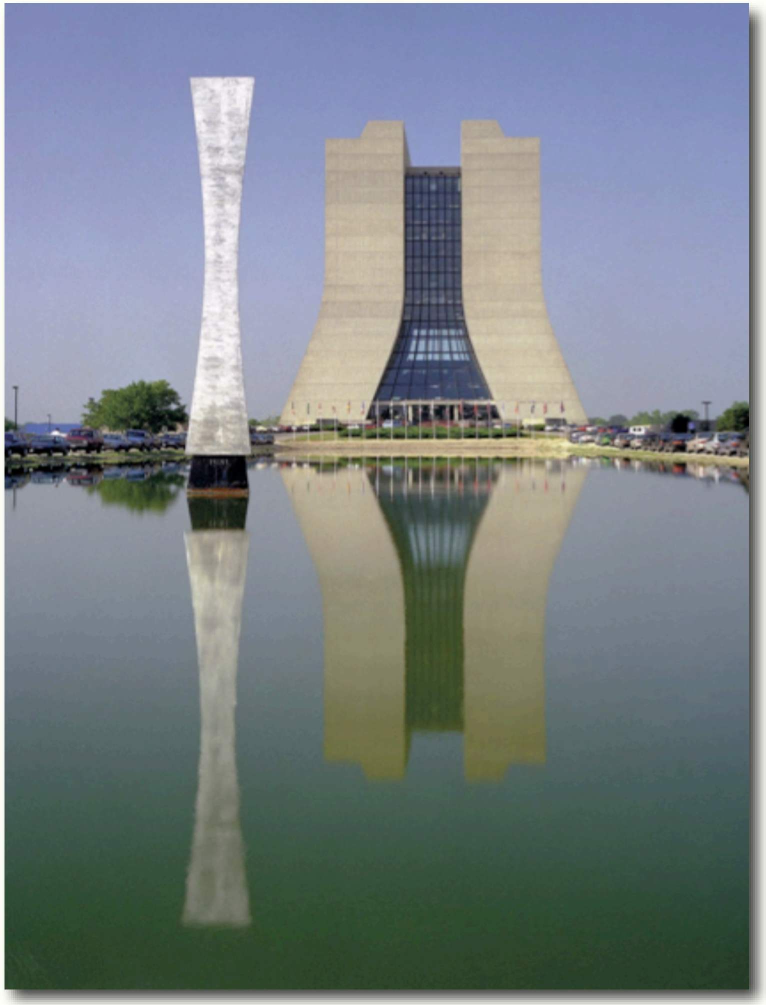
B_s Oscillations and Rare Decays at the Tevatron



GDR SUSY Workshop

28. April 2008 Strasbourg

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Outline

- Motivation
- Measurement of Bs mixing: Δm_s
- Measurement of $\Delta\Gamma$
- CP Violation in the B_s system
- Rare leptonic decays
- b->llX transitions
- Summary

Motivation

Why huge
matter-antimatter asymme
in the universe?

Why B Physics? - It's got it all!

- Electroweak symmetry breaking → determines flavor structure: CKM matrix, CP violation, FCNC's
- QCD Modeling: production, spectroscopy, masses, lifetimes, decays → Challenges lattice gauge, Heavy Quark Effective Theory, strong symmetries
- Search for new physics → rare decays and

Why at the Tevatron?

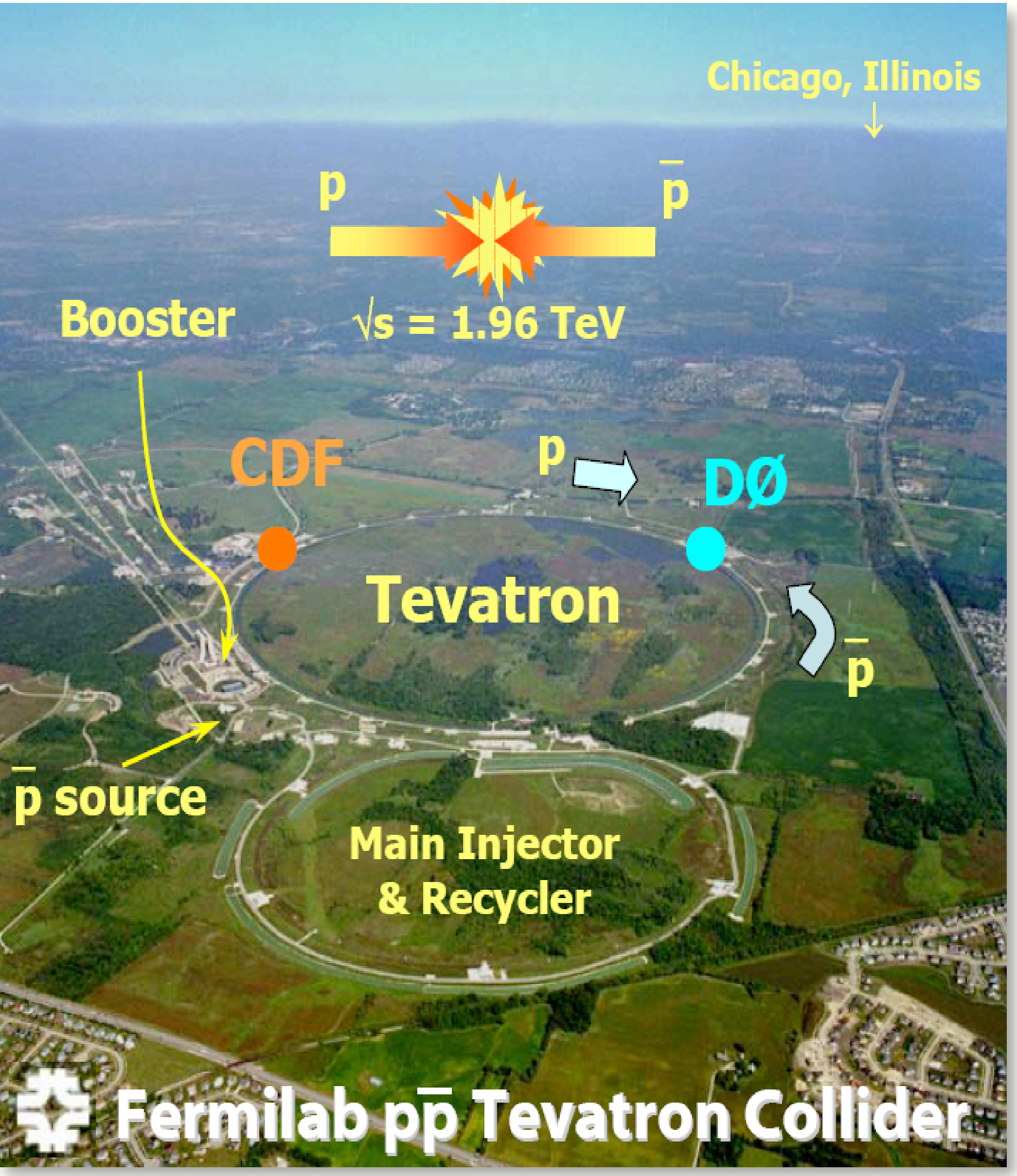
$\bar{b}\,s$ $\quad \bar{b}\,c$ $\quad d\,\bar{b}$ $\quad s\,\bar{b}$ $\qquad\qquad b\,u\,d$ $\quad b\,u\,u$ $\quad b\,u\,u$

$\boxed{B_s^0}$, B_c, B^{**}, B_s^{**}, ... $\qquad \Lambda_b$, Σ_b, Ξ_b, ...

→ Complementary to $\Upsilon(4S)$ B factories

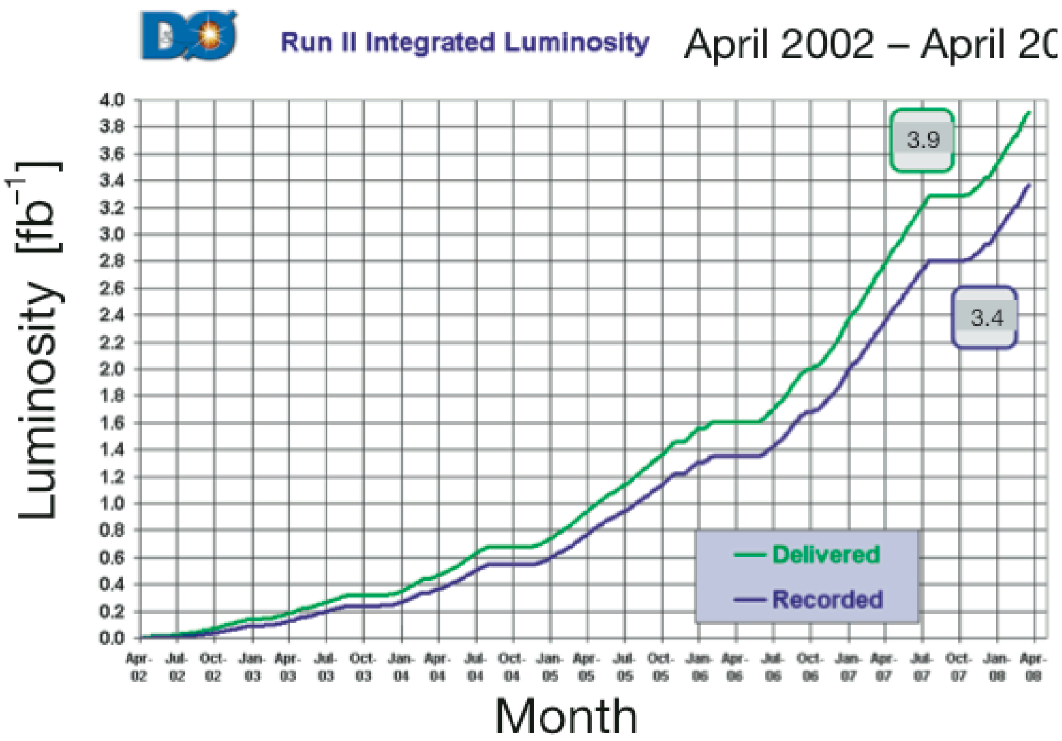
$\bar{b}\,d$ $\quad B_d^0$, B^+ $\quad \bar{b}\,u$

Tevatron

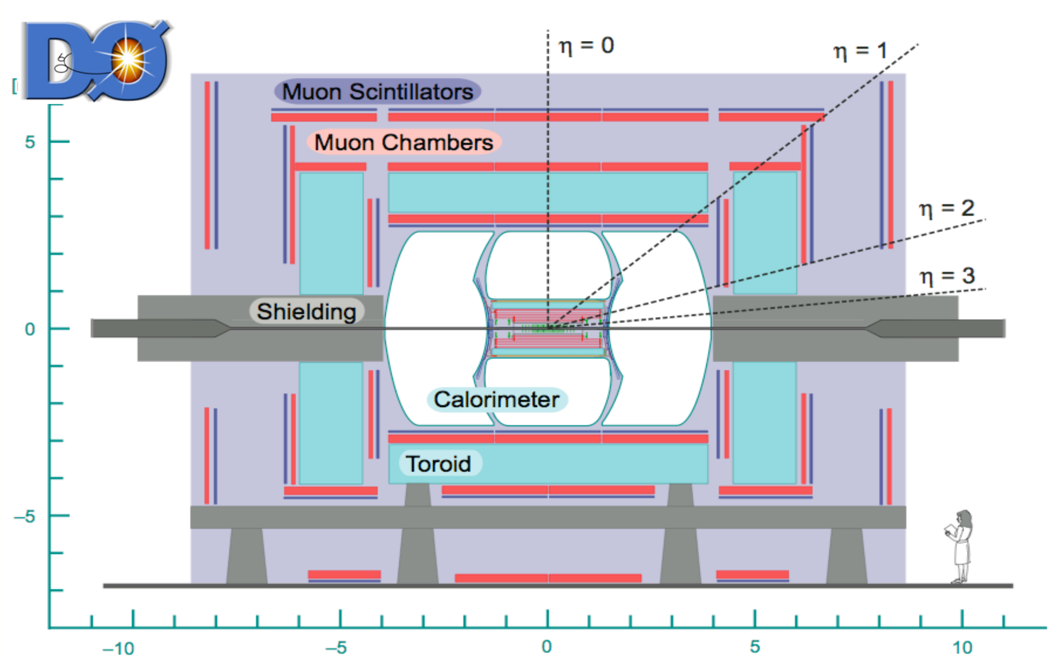


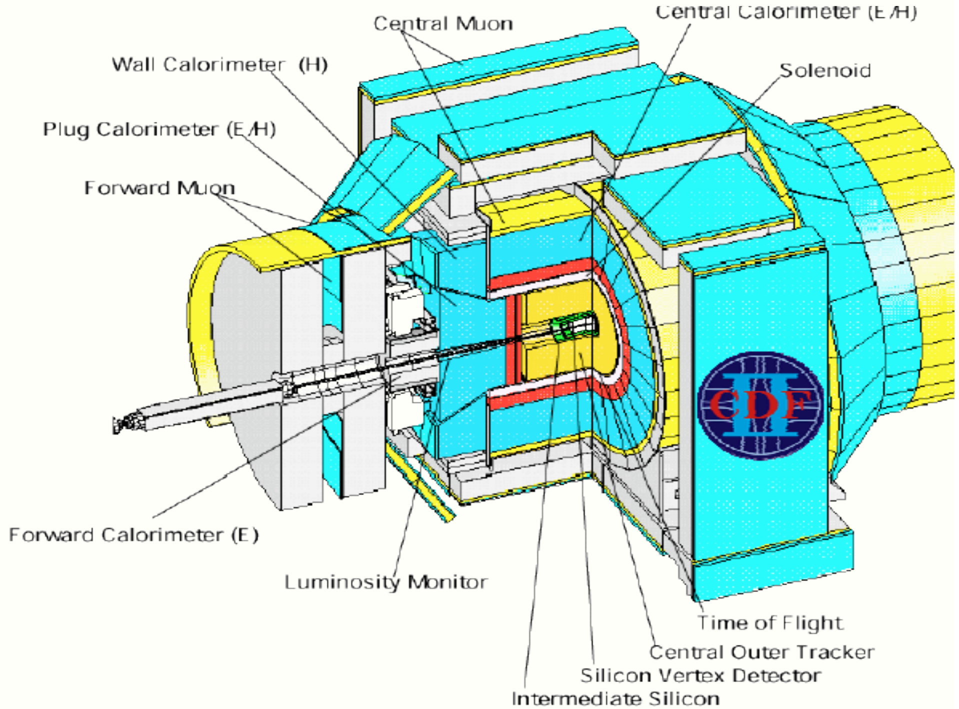
Tevatron continues to perform well

- Over 3.9fb^{-1} delivered and 3.4fb^{-1} recorded by each experiment, 2.8f analysed
- Peak luminosities of ~3 x10^{32} cm^{-2} s
  → up to 10 interactions



Detectors





Relevant for B physics:

DØ Tracker: excellent coverage & vertexing

- Silicon & scintillating fiber
- Small radii, but extending to $|\eta| < 2$
- New Layer 0 silicon on beam pipe in 2006, improving impact para. resol.
- Triggered muon coverage: $|\eta| < 2$
- E.g.triggers: dimuons, single muons, track displacement @ L2

CDF Tracker: excellent mass resolution & vertexing

- Silicon, Layer 00
- Large radii drift chamber, many hits, excellent momentum resolution
- dE/dx (and TOF): particle id
- Triggered muon coverage: $|\eta| < 1$
- E.g.triggers: dimuons, lepton + displ. track, two displaced tracks

Mixing and Oscillations

All different!

Weak Eigenstates propagate according to Schrodinger:

$$i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

Diagonalize

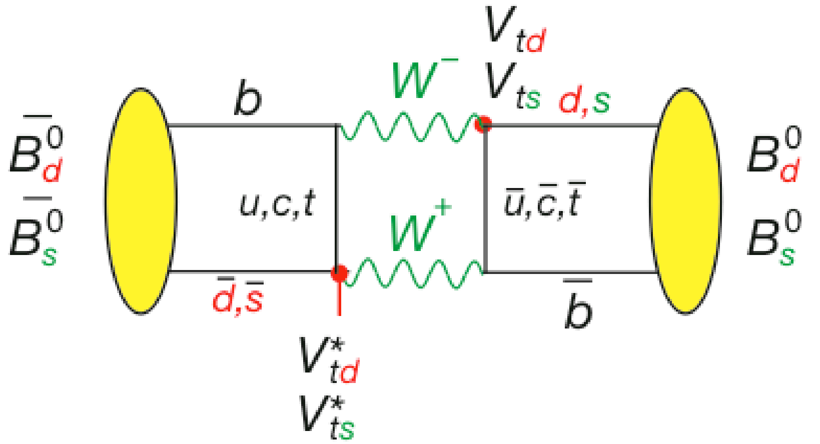
CP Eigenstates: $|B^{odd}\rangle = |B^0\rangle + |\bar{B}^0\rangle$ $\quad |B^{even}\rangle = |B^0\rangle - |\bar{B}^0\rangle$

Mass Eigenstates: $|B^H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$ $\quad |B^L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$

Heavy *Light*

Mass Difference:

$$\Delta m = M_H - M_L \sim 2|M_{12}|$$



slow oscillation

fast oscillation

Conversion of matter to anti-matter

Mixing and Oscillations

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Heavy *Light*

For the B_s^0 meson:

$$\Delta m_s = M_H - M_L \sim 2|M_{12}|$$

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$$

Tiny for B_d^0 meson, but not for B_s^0 ! eigenstates propagate with different lifetimes!

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \; ; \quad \tau_s = \frac{1}{\Gamma_s}$$

$$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004 \text{ in SM}$$

Mixing and Oscillations

All different!

Weak Eigenstates propagate according to Schrodinger:

$$i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

Probe entire matrix

Diagonalize

CP Eigenstates: $|B^{odd}\rangle = |B^0\rangle + |\bar{B}^0\rangle$ $\quad |B^{even}\rangle = |B^0\rangle - |\bar{B}^0\rangle$

Mass Eigenstates: $|B^H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$ $\quad |B^L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$

Heavy Light

For the B_s^0 meson: Whole new window for New physics

$$\Delta m_s = M_H - M_L \sim 2|M_{12}|$$

Sensitive for NP

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

Not sensitive for NP

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$$

Very sensitive for NP

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \quad ; \quad \bar{\tau}_s = \frac{1}{\Gamma_s}$$

$$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004 \text{ in SM}$$

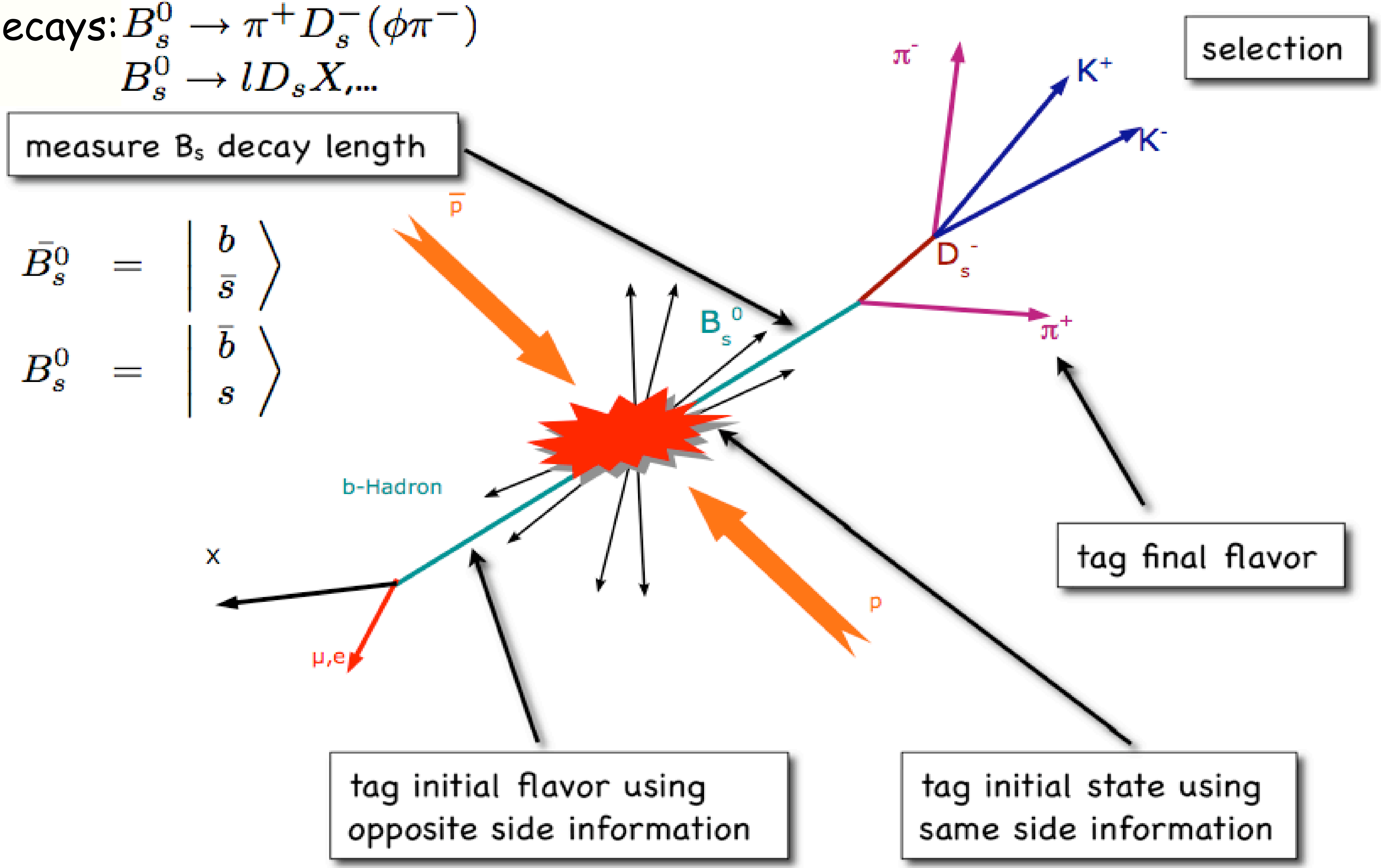
Frequency of Oscillations

Decays: $B_s^0 \to \pi^+ D_s^- (\phi\pi^-)$

$B_s^0 \to l D_s X$,...

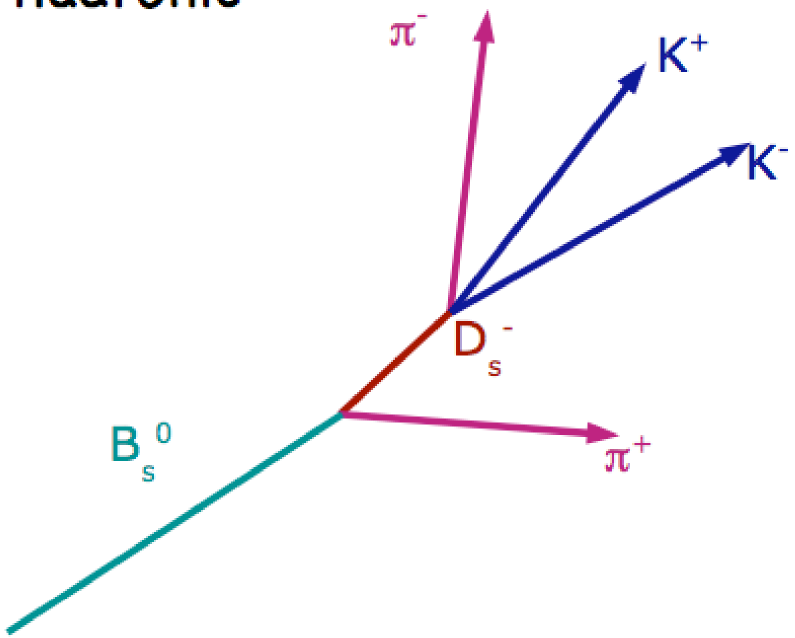
$$\bar{B}_s^0 = \left| \begin{matrix} b \\ \bar{s} \end{matrix} \right\rangle$$

$$B_s^0 = \left| \begin{matrix} \bar{b} \\ s \end{matrix} \right\rangle$$



Decay channels

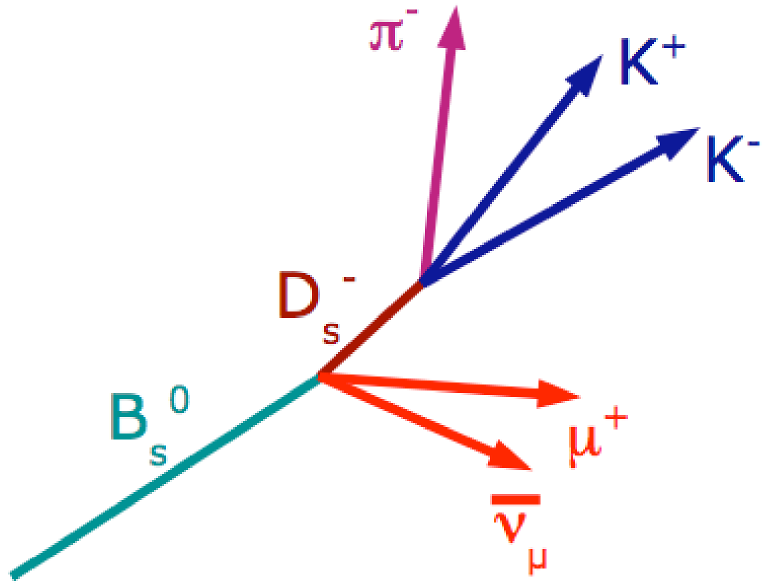
hadronic



- all decay particles reconstructable
  → better time resolution
- low event rate
- higher combinatoric

more sensitive at higher Δm_s

semileptonic

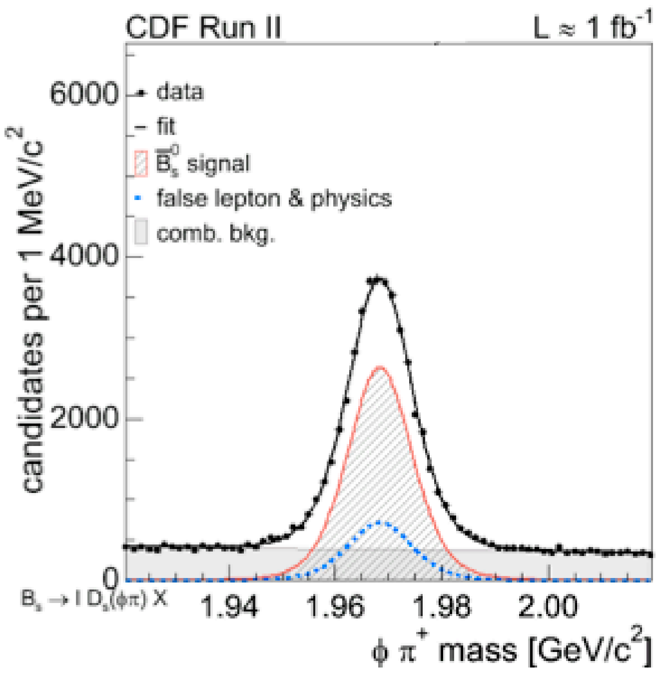


- high event rate
- ν_μ momentum not measurable
  → sensitivity proper time limited by momentum measurement

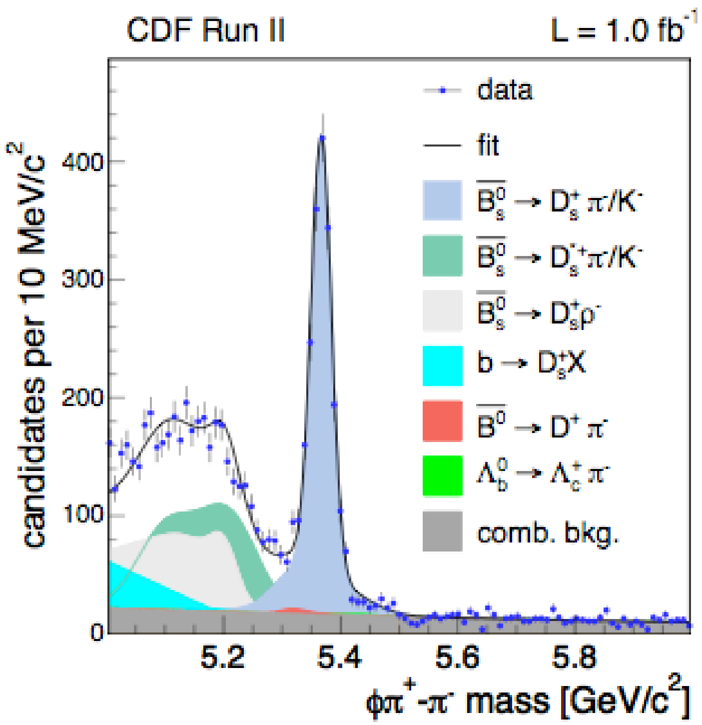
more sensitive at lower Δm_s

CDF Signal Selection

$$B_s \to \mu^+ D_s^- (\phi\pi) X$$



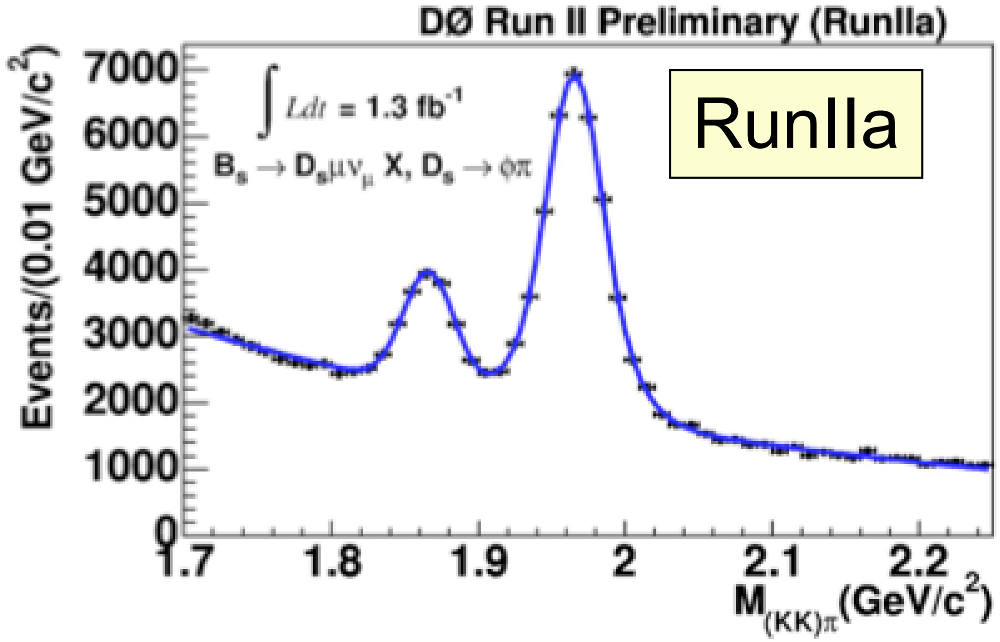
$$B_s \to \pi^+ D_s^- (\phi\pi)$$



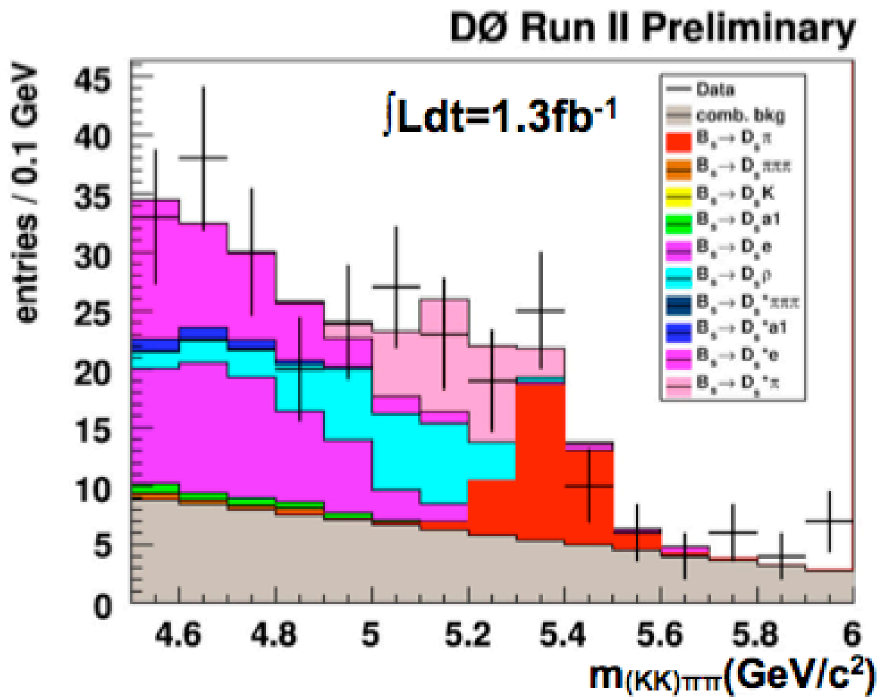
DØ Signal Selection

$$B_s \to \mu^+ D_s^- (\phi\pi) X$$

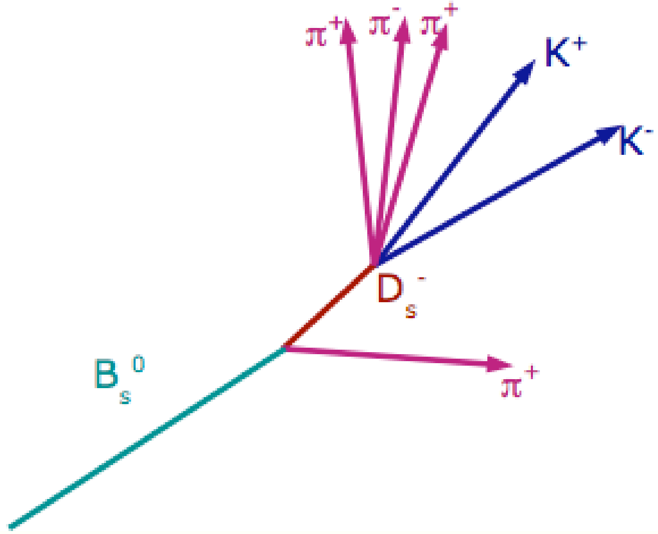
64500 semileptonic events



$$B_s \to \pi^+ D_s^- (\phi\pi) X$$



Only 250 reconstructed and tagged hadronic events (CDF ~500)



Decay channels

CDF (data sample size: $\int Ldt$ = 1fb^{-1}):

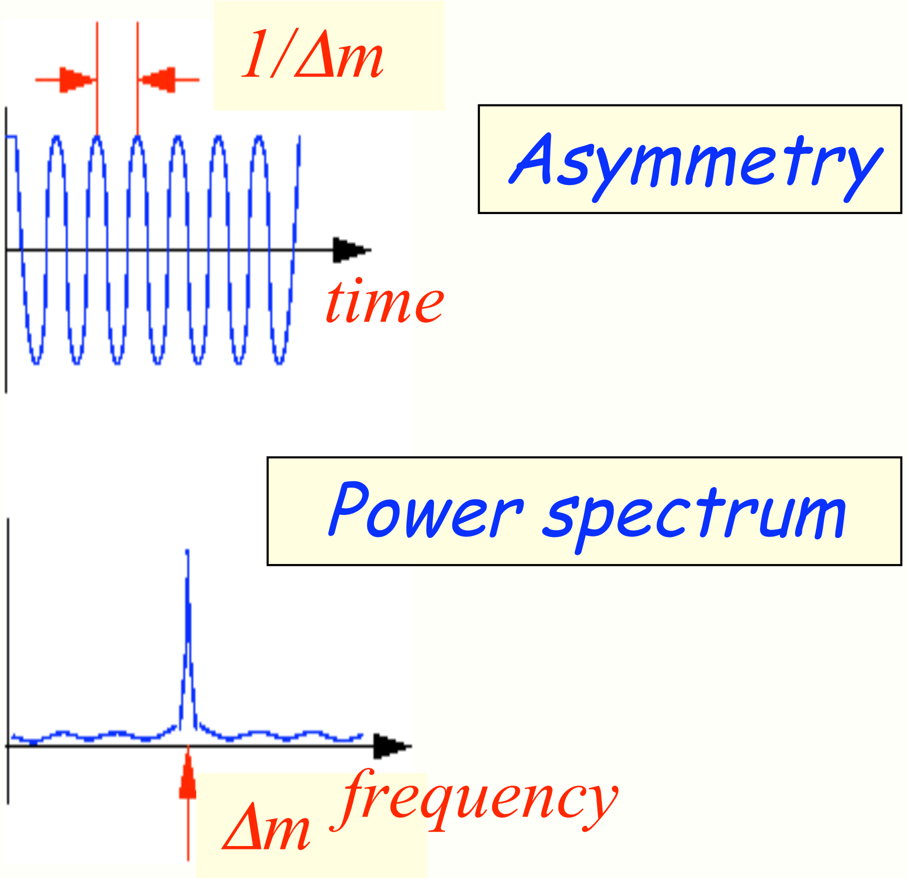
channel	candidates
$\bar{B}_s \to l D_s X$	61500
$\bar{B}_s \to \pi^- D_s^+(\phi\pi^+)$	2000
$\bar{B}_s \to \pi^- D_s^+(K^*(892)^0 K^+)$	1400
$\bar{B}_s \to \pi^- D_s^+(\pi^+\pi^-\pi^+)$	700
$\bar{B}_s \to \pi^-\pi^+\pi^- D_s^+(\phi\pi^+)$	700
$\bar{B}_s \to \pi^-\pi^+\pi^- D_s^+(K^*(892)^0 K^+)$	600
$\bar{B}_s \to \pi^-\pi^+\pi^- D_s^+(\pi^+\pi^-\pi^+)$	200
partially reconstructed	3100

DØ (bigger dataset also includes resolution improvement through Layer0):

channel	candidates	improvements
$B_s \to \mu^+ D_s^-(\phi\pi)X$	44777±415	data: 1.3 fb^{-1} → 2.4 fb^{-1}
$B_s \to e^+ D_s^-(\phi\pi)X$	1663±102	data: 1.3 fb^{-1} → 2.4 fb^{-1}
$B_s \to \pi^+ D_s^-(\phi\pi)X$	249±17	new channel
$B_s \to \mu^+ D_s^-(K^{*0}K^-)X$	18098±903	data: 1.3 fb^{-1} → 2.4 fb^{-1}

Amplitude scan

$$\boxed{P(\Delta m_s) \approx 1 \pm \cos \Delta m_s t \Rightarrow P(A) \approx 1 \pm A \cos \Delta m_s t}$$



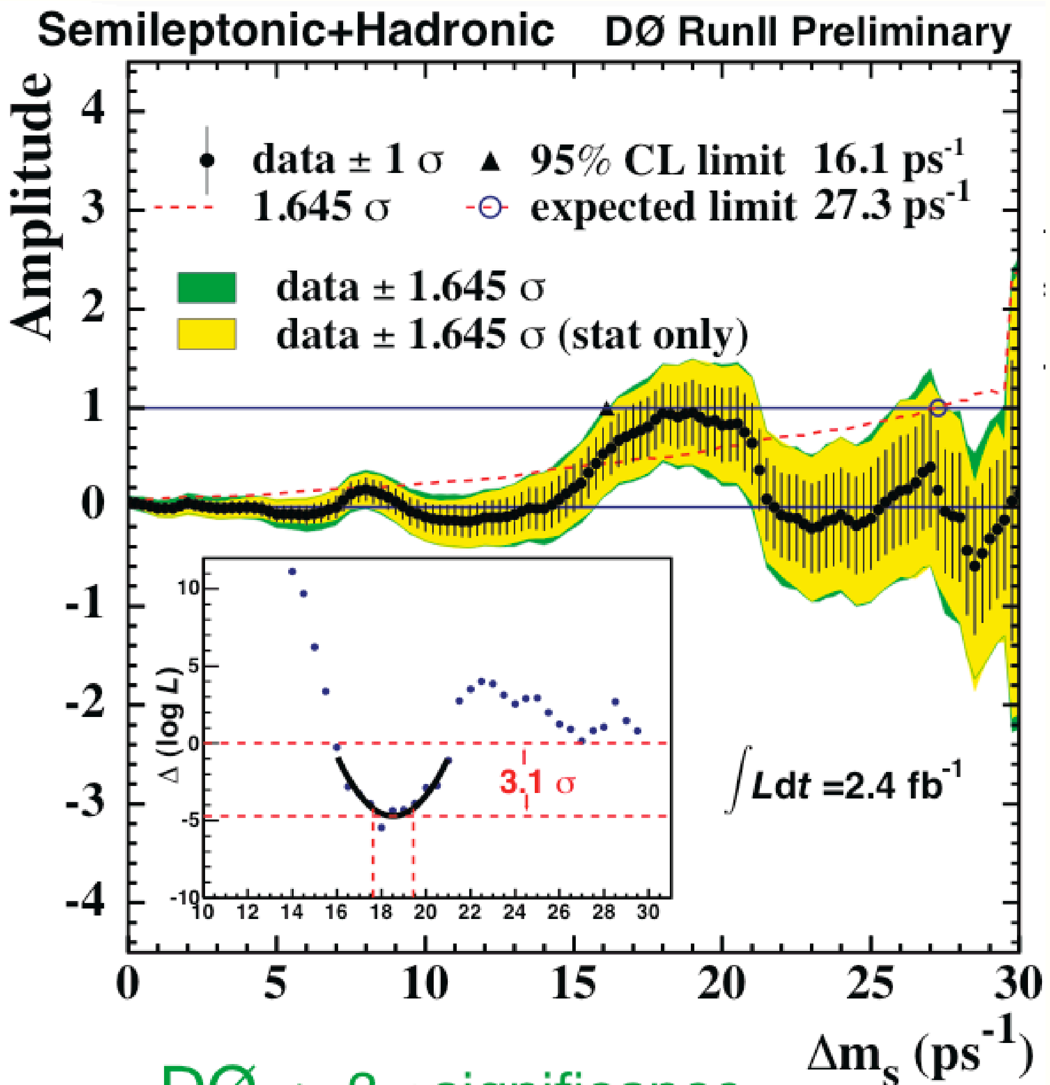
Motivation is to simplify combining results with other experiments

Purity of flavor tag

$$\mathrm{Prob}^{unmix,mix}(x) = \frac{K}{2c\tau_{B_s}} \exp\left(-\frac{Kx}{c\tau_{B_s}}\right)\left(1 \pm (1-2\eta)\, A \cos(\Delta m_s K x / c)\right)$$

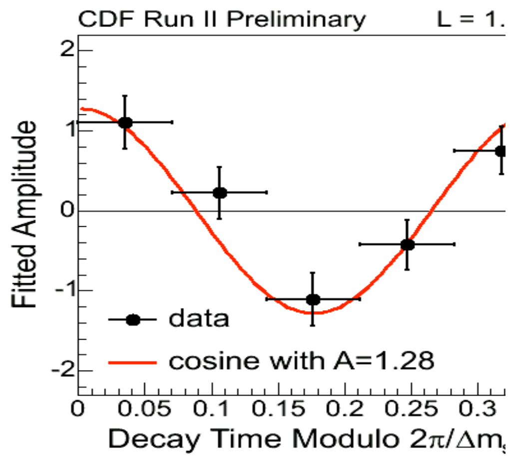
Amplitude

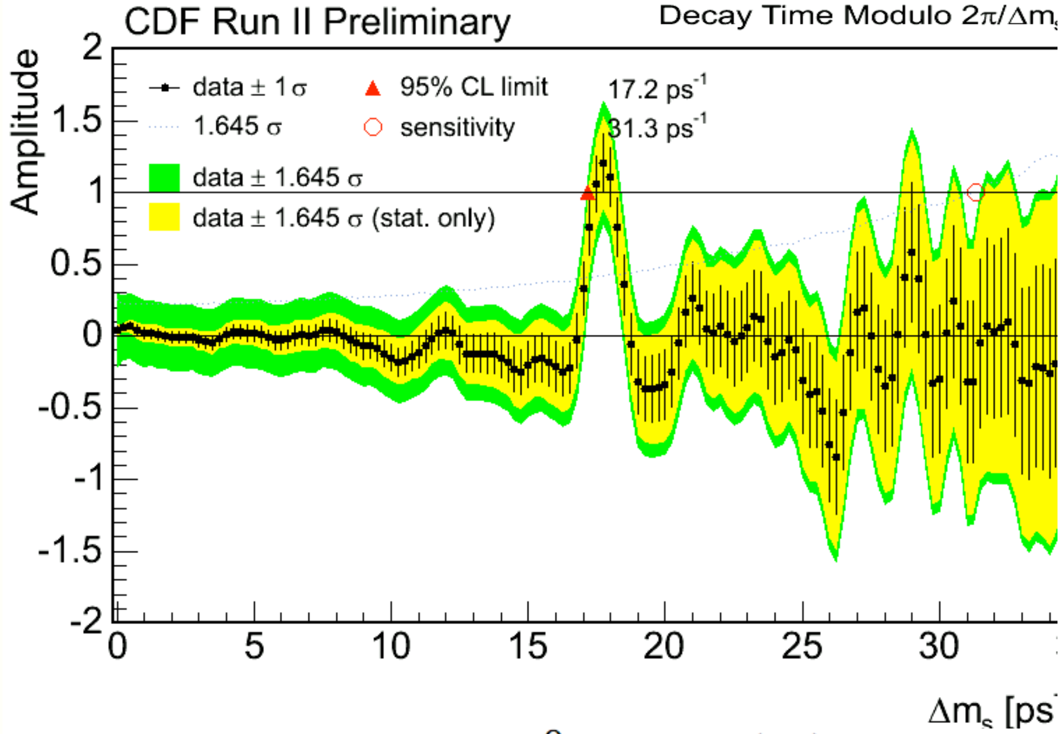
B_s: Δm_s, Frequency of Osci.



DØ, > 3σ significance

$$\Delta m_s = 18.56 \pm 0.87\, ps^{-1}$$





Power of hadronic $B_s^0 \to D_s\pi(X)$ decay mo
& two-displace track trigger

CDF, > 5σ significance

$$\Delta m_s = 17.77 \pm 0.12\, ps^{-1}$$

CP Violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

In the SM CP violation occurs in only one place:
complex phases in unitary CKM matrix; NP, plenty of places!!!

e.g. 43 in MSSM

CP Violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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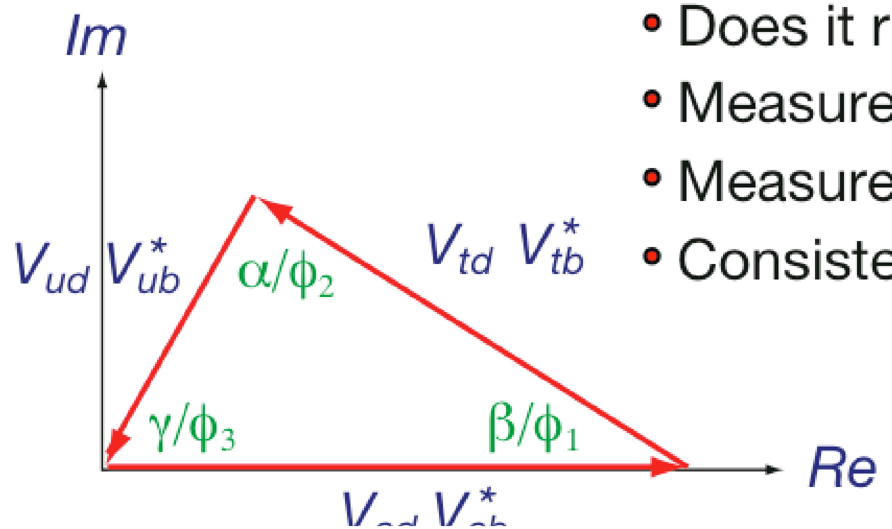
B_d unitarity condition $\quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



- Does it return to zero?
- Measure lengths of all sides
- Measure all three angles
- Consistent?

CP Violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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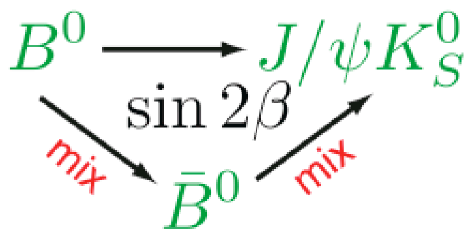
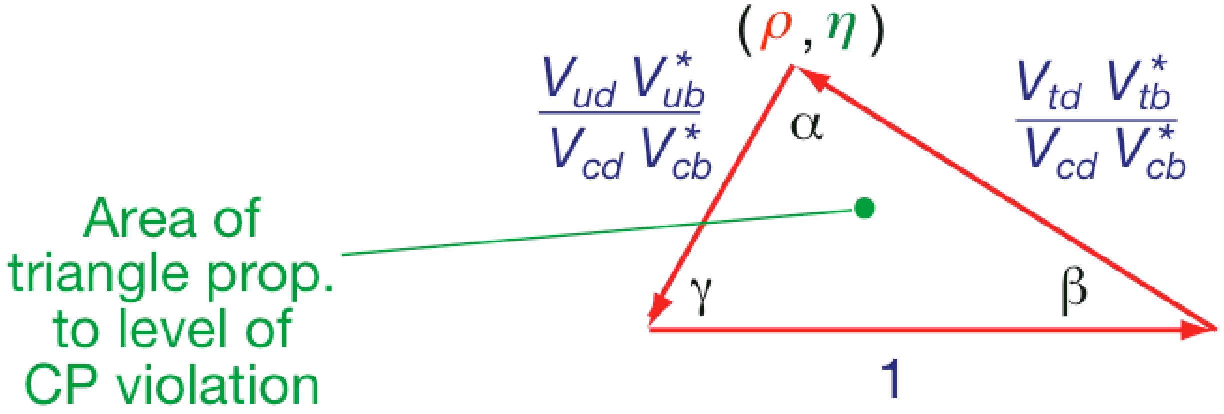
B_d unitarity condition

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Golden mode,
B factories

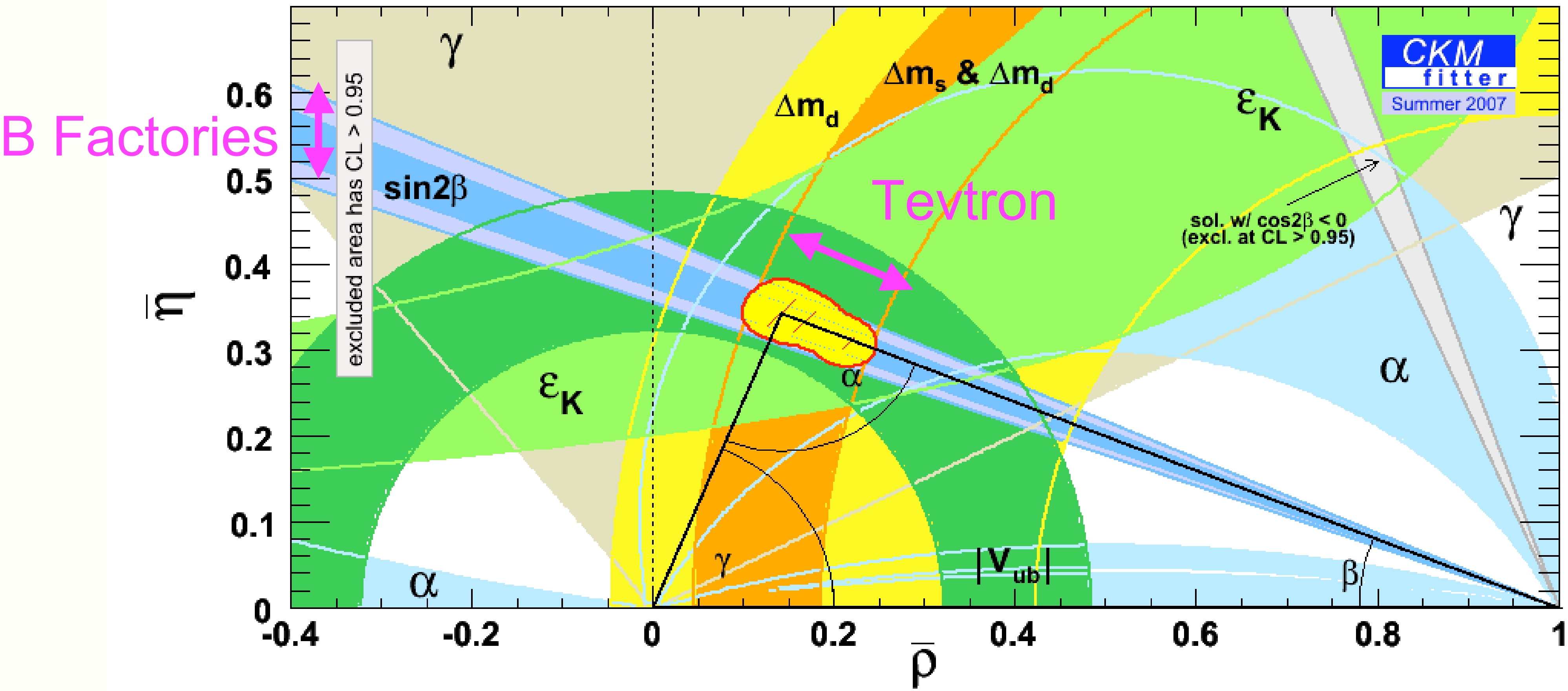


CP violation through
interference of diagrams
with and w/o mixing



B_s: Δm_s, Frequency of Osci

$$\frac{\Delta m_s}{\Delta m_d} = V_{td}$$



Not much room for New Physics!

Measurement of $\Delta\Gamma$

First assume no CP violatio
in B_s mixing, Φ_s=0

CP and mass eigenstates are the sar

- $B_s \rightarrow D_s^{(*)} D_s^{(*)}$
  - Three channels
    - [$D_s D_s$ (PP), $D_s^* D_s$ (VP), $D_s^* D_s^*$ (VV)]
  - Heavy quark limit + factorization
    - $B_s^{odd} \rightarrow D_s^* D_s$ is forbidden
  - $D_s^* D_s^*$ in S-wave
  - $\Rightarrow$ $Ds^{(*)} Ds^{(*)}$ pure CP even

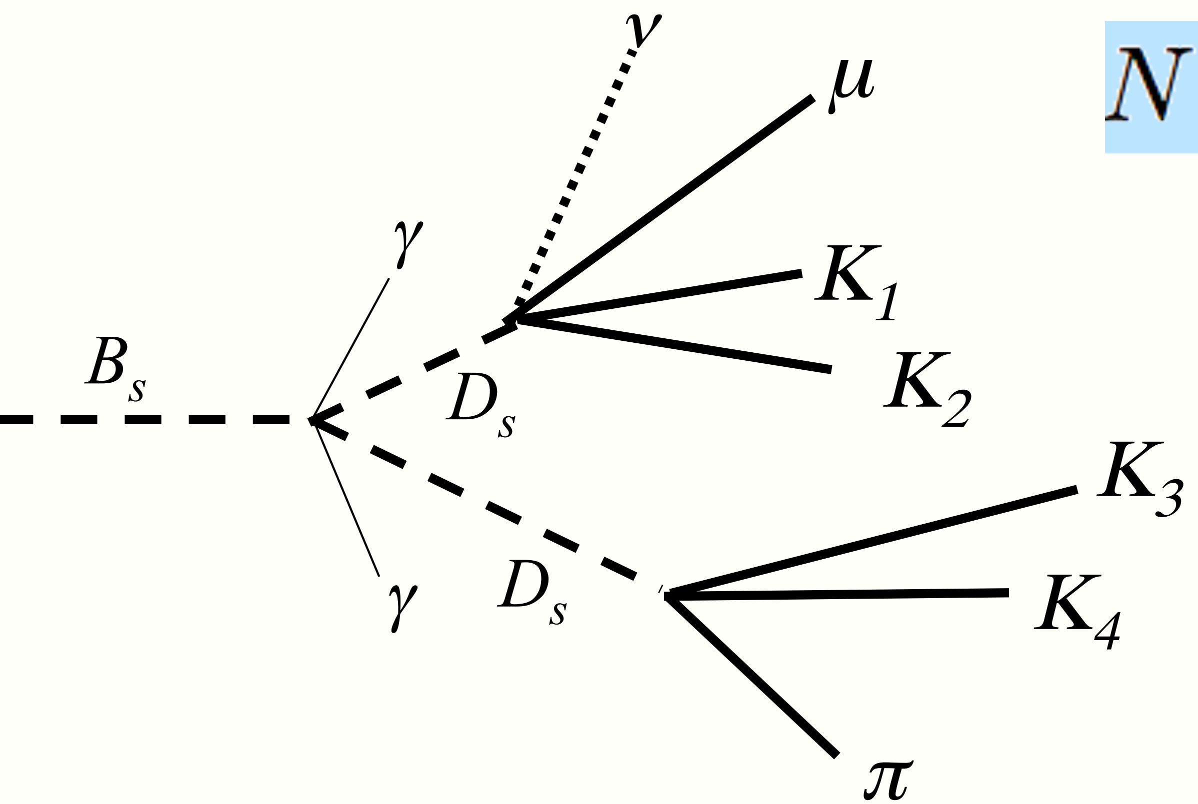
$$BF(B_s \rightarrow D_s^{(*)} D_s^{(*)}) = \left(\frac{\Delta\Gamma_{CP}}{2\Gamma}\right)\left(1 + \mathrm{O}\left(\frac{\Delta\Gamma}{\Gamma}\right)\right)$$

- Flavor specific B_s lifetime
  - *Flavor specific decays carry equal amounts of B_H and B_L*
  - *Get flavor specific lifetime if FS data with is fit w/ single exponential*

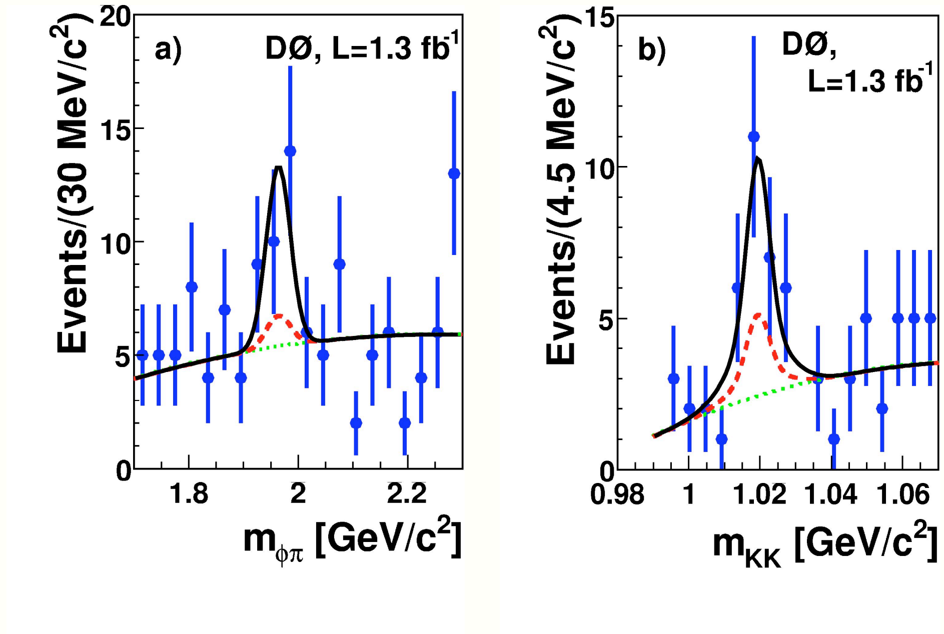
$$e^{-t/\tau_{FS}} = \frac{1}{2} \cdot \left(e^{-t/\tau_H} + e^{-t/\tau_L}\right)$$

- $B_s \rightarrow J/\psi\ \phi$: $P \rightarrow VV$
  - Even and odd paths distinguishable with angular analysis of final state particles

$\Delta\Gamma$ from $B_s \to D_s^{(*)} D_s^{(*)}$

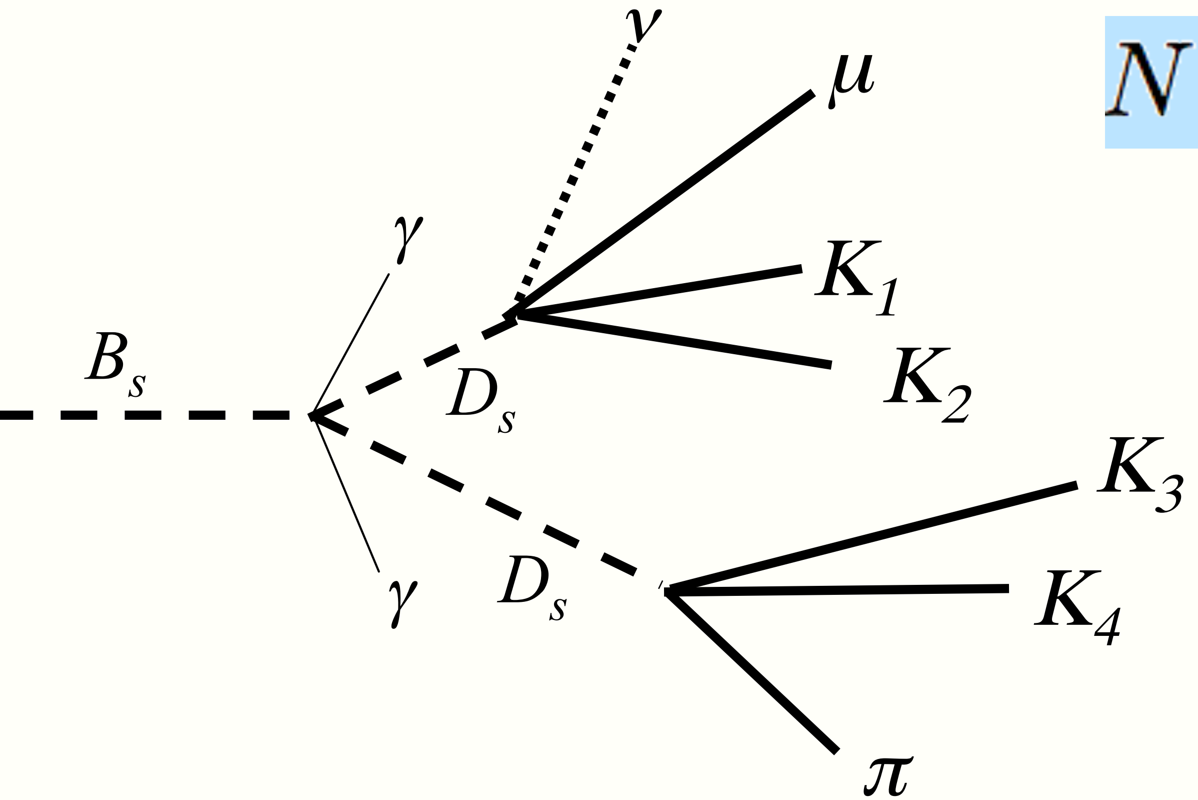


$$N(D_s^{(*)} D_s^{(*)}) = 13.4\ ^{+6}_{-6}$$

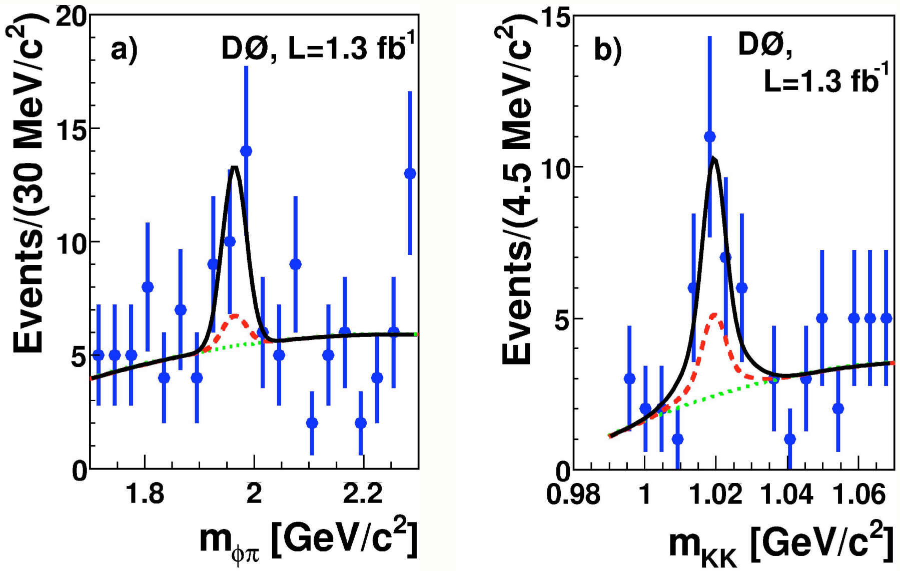


- Trigger on muon from semileptonic D_s decay
- Ignore any photons
- Look for correlated production of $D_s \to \phi\pi$ and $D_s \to \phi\mu$

$\Delta\Gamma$ from $B_s \to D_s^{(*)} D_s^{(*)}$



$$N(D_s^{(*)} D_s^{(*)}) = 13.4 \begin{array}{l} +6 \\ -6 \end{array}$$



$$BF(B_s \to D_s^{(*)} D_s^{(*)}) = 0.039^{+0.019}_{-0.017}\,{}^{+0.016}_{-0.015}$$

$$\frac{\Delta\Gamma_{CP}}{\Gamma} = 0.079^{+0.038}_{-0.035}\,{}^{+0.031}_{-0.030}$$

B_s Flavor Specific Lifetime

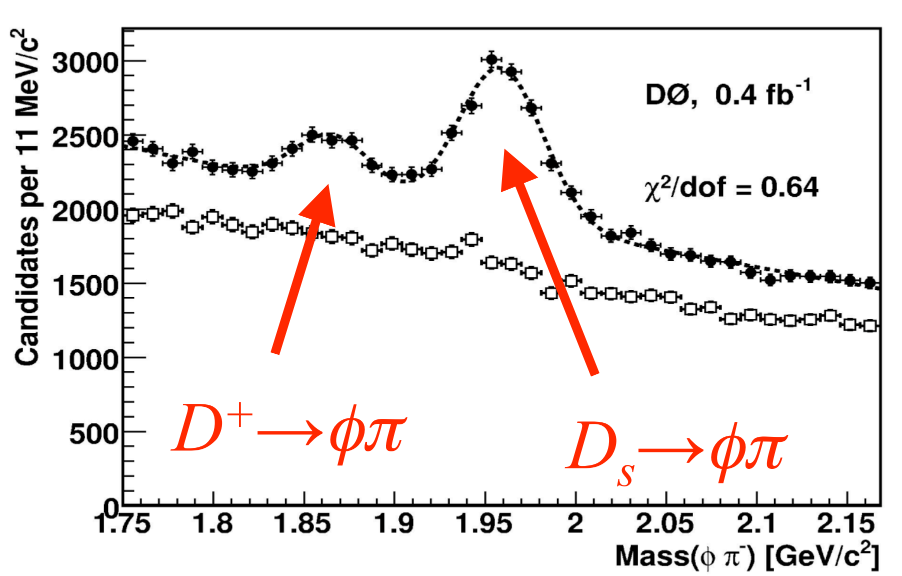
Know flavor at time of decay from charge of decay product

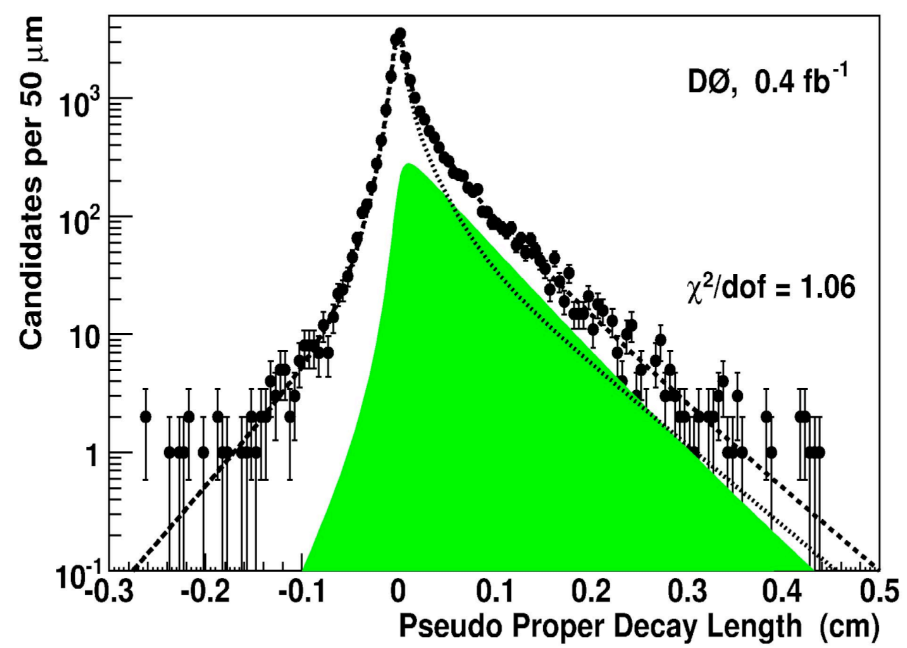
hep-ph/0201071

$$|B_s \to D_s^{-} \mu^{+} \nu\rangle = \frac{1}{\sqrt{2}}\left(|B_H\rangle + |B_L\rangle\right)$$

50% CP-even, 50% CP-odd at time t

$$\boxed{\tau_{FS} = \frac{1}{\bar{\Gamma}_s}\frac{1+y^2}{1-y^2} \text{ with } y = \frac{\Delta\Gamma}{2\Gamma}}$$



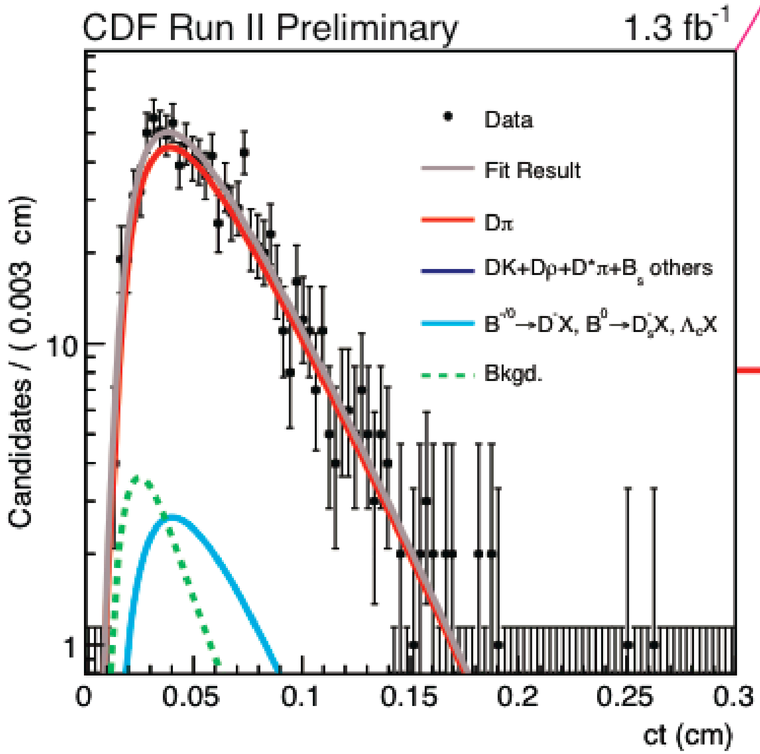


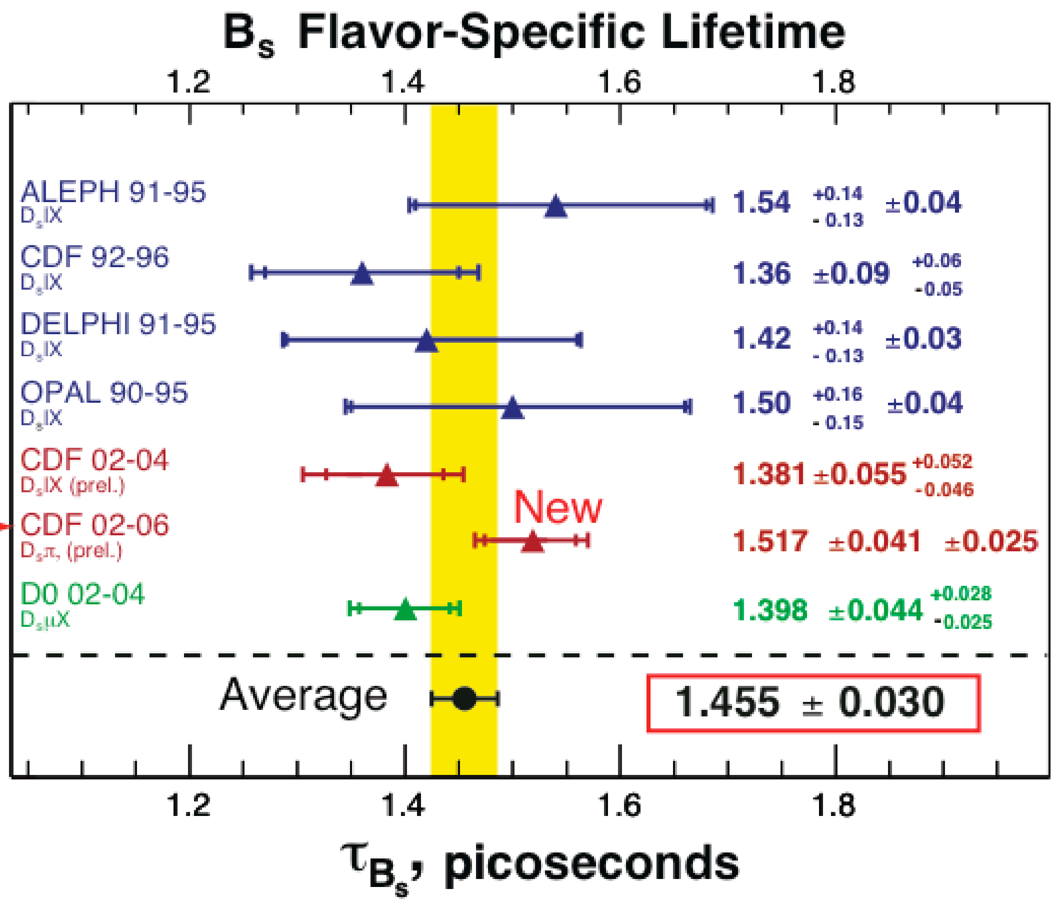
$$\boxed{\tau_{FS}(B_s) = 1.381 \pm 0.055^{+0.052}_{-0.046}\, ps}$$

B_s Flavor Specific Lifetime

$$|B_s \rightarrow D_s^- \pi^+(\pi^0)\rangle = \frac{1}{\sqrt{2}}\Big(|B_H\rangle + |B_L\rangle\Big)$$

CDF, 1.6 fb^{-1}, CDF Note 9015

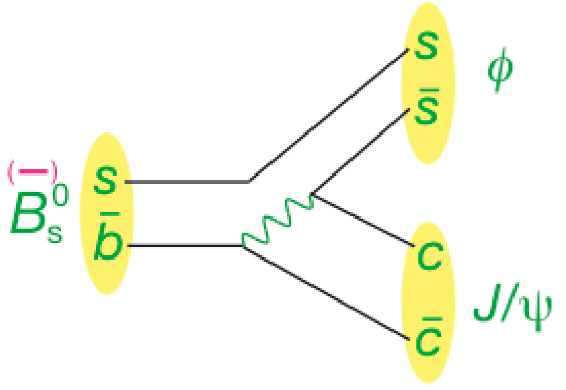




$B_s \to J/\psi\ \phi$

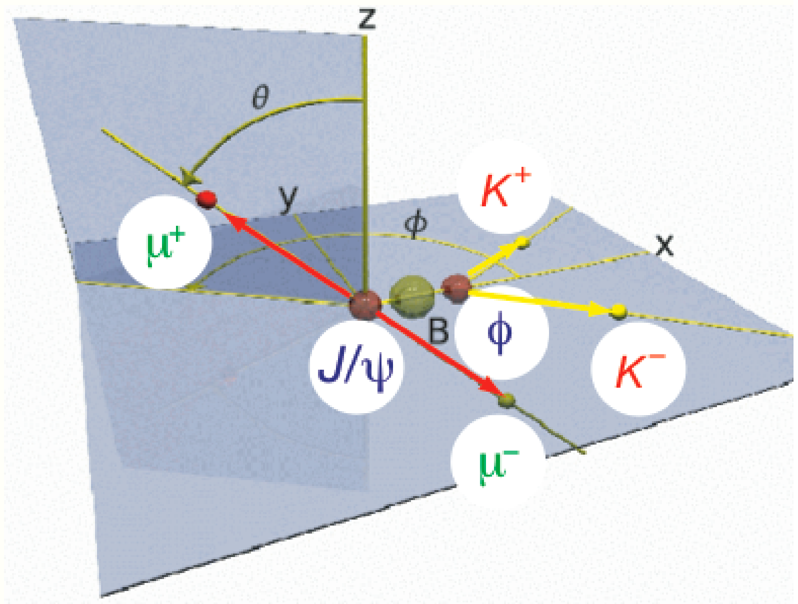
- Heavy (H, CP-odd) and Light (L, CP-even) B_s states

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H; \quad \Gamma_s = (\Gamma_L + \Gamma_H)/2; \quad \bar{\tau}_s = \frac{1}{\Gamma_s}$$



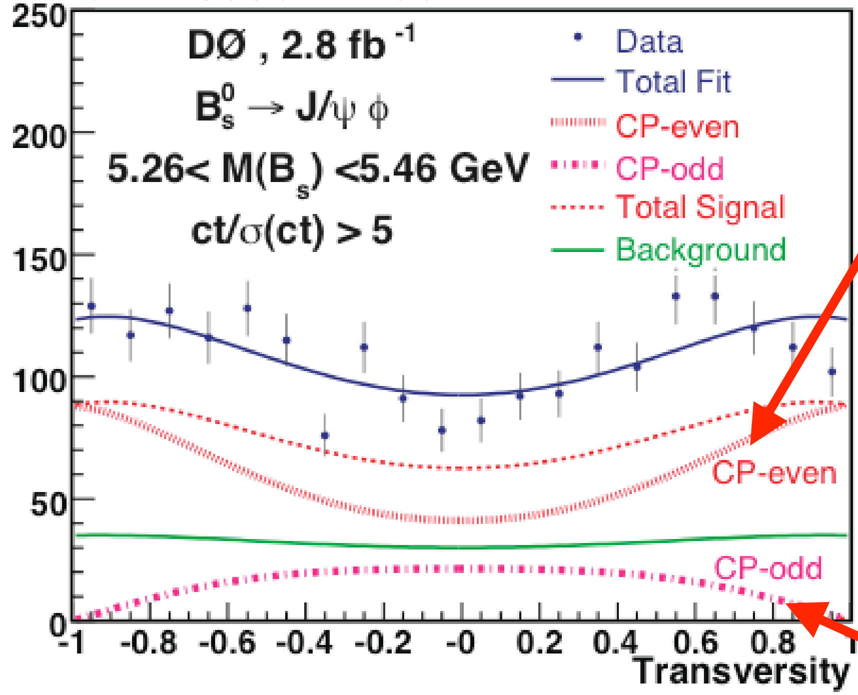
Not "flavor specific", predicted to be more CP even than odd

- Decays into two vector mesons that are either *CP*-odd (*L*=1) or *CP*-even (*L*=0,2)
- Time-dependent angular distributions allow separation of components
- Simultaneous fit to lifetime and three angles



$B_s \to J/\psi\ \phi$

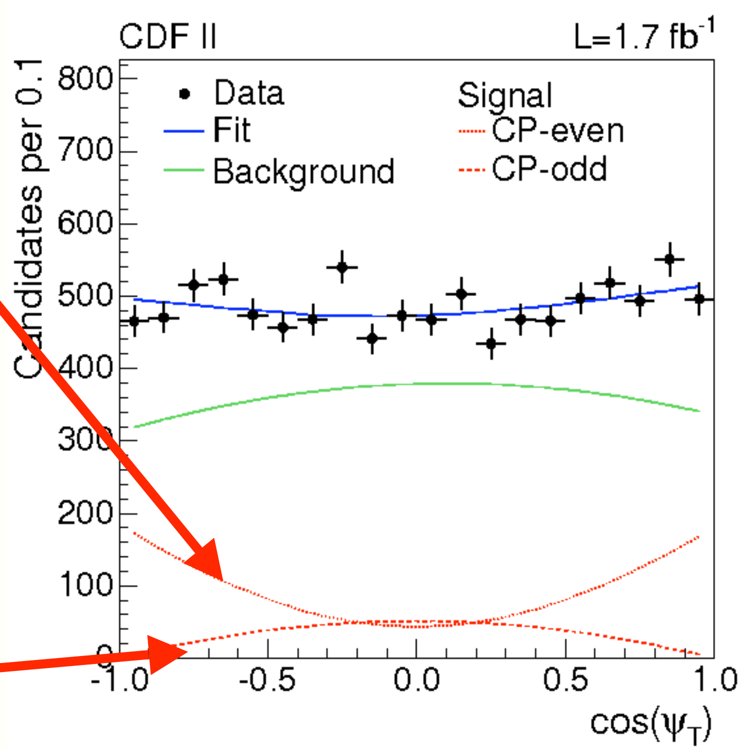
arXiv:/0802.2255

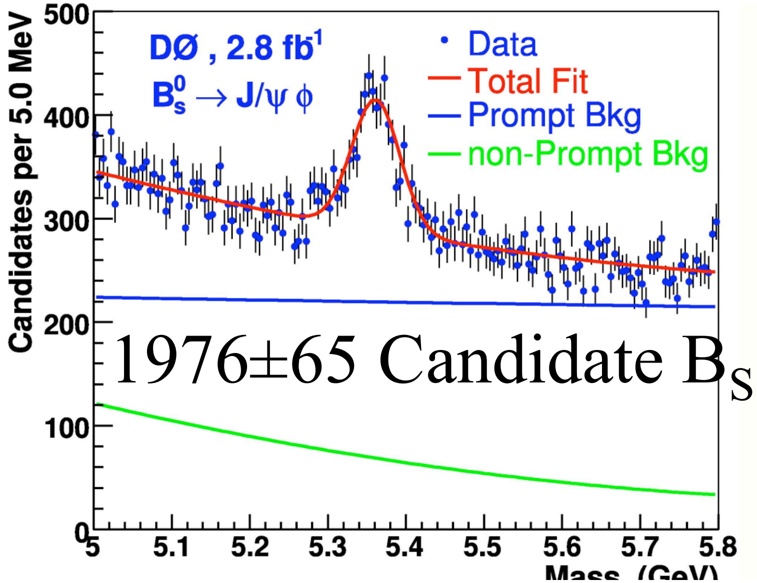


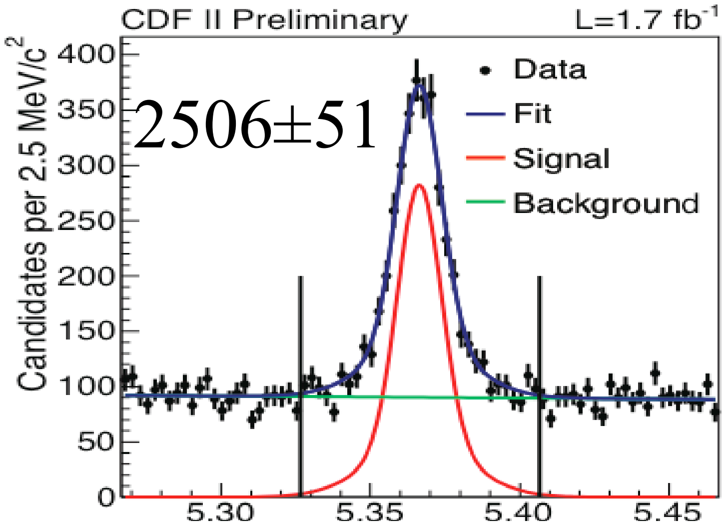
even / light

odd / heavy

arXiv:/:0712.2348



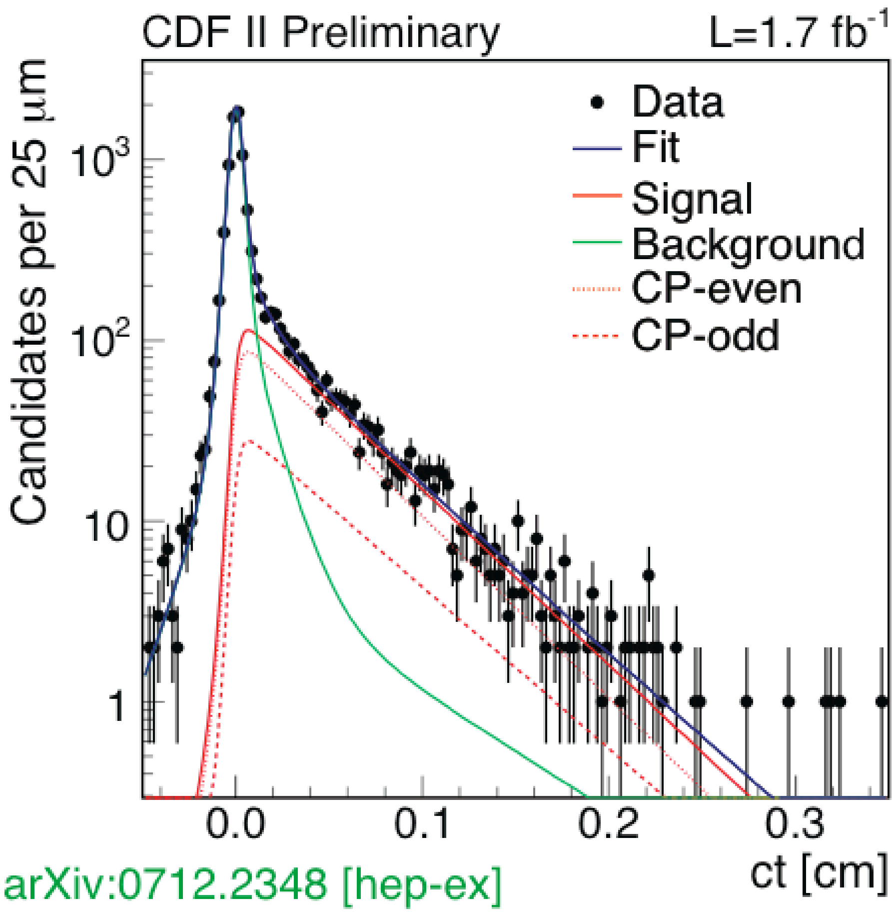




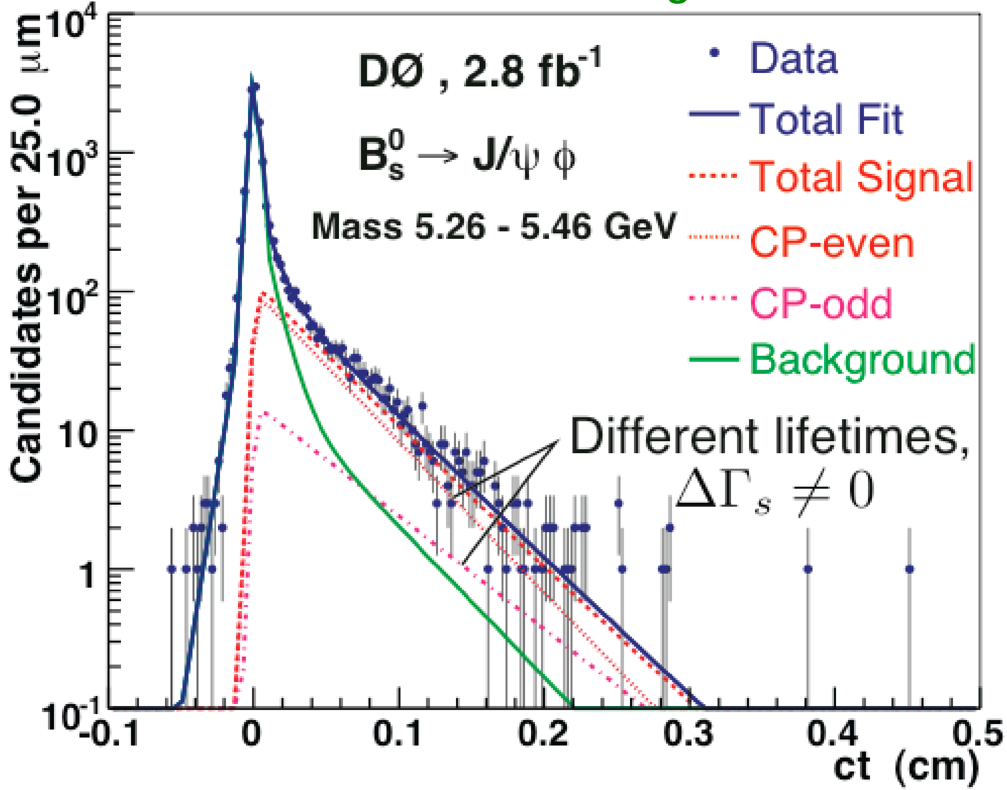
$\Delta\Gamma$ and Γ_s

First assume no CP violatio
in B_s mixing, Φ_s=0

CP and mass eigenstates are the s



arXiv:0712.2348 [hep-ex]



arXiv:0802.2255 [hep-ex]

$$\Delta\Gamma_s = 0.076^{+0.059}_{-0.063} \pm 0.006\,\mathrm{ps}^{-1}$$

$$\bar{\tau}_s = 1.52 \pm 0.04 \pm 0.02\,\mathrm{ps}$$

$$\Delta\Gamma_s = 0.14 \pm 0.07\,\mathrm{ps}^{-1}$$

$$\bar{\tau}_s = 1.53 \pm 0.05 \pm 0.01\,\mathrm{ps}$$

$$\bar{\tau}_s = \frac{1}{\Gamma_s} = \frac{2}{\Gamma_H + \Gamma_L}$$

c.f. $\Delta\Gamma_s^{SM,pred} = 0.088 \pm 0.017\,\mathrm{ps}^{-1}$ (hep-ph/0612167)

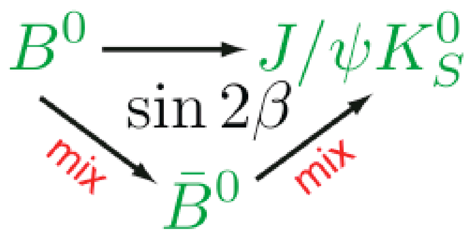
CP Violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

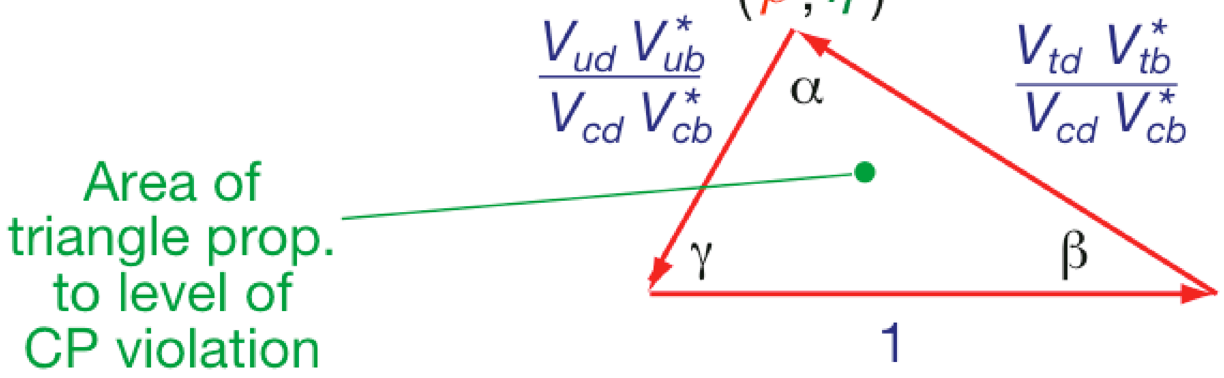
In the SM CP violation occurs in only one place:
complex phases in unitary CKM matrix; NP, plenty of places!!!

B_d unitarity condition $\quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

Golden mode,
B factories



CP violation through
interference of diagrams
with and w/o mixing



CP Violation in B_s System

Explore new part of matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & \boxed{V_{us}} & \boxed{V_{ub}} \\ V_{cd} & \boxed{V_{cs}} & \boxed{V_{cb}} \\ V_{td} & \boxed{V_{ts}} & \boxed{V_{tb}} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

In the SM CP violation occurs in only one place:
complex phases in unitary CKM matrix; NP, plenty of places!!!

B_s unitarity condition

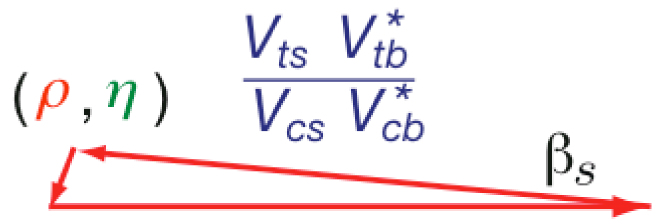
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$\beta_s^{SM} = \arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$$

$$\approx 0.02$$

Tiny!

"Squashed" Triangle



CP Violation in B_s System

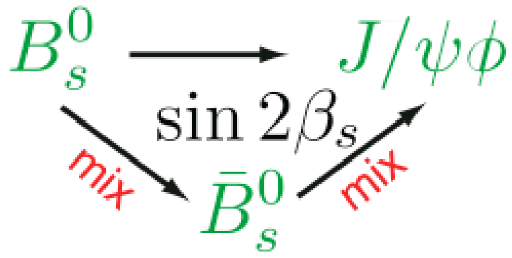
Explore new part of matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

In the SM CP violation occurs in only one place:
complex phases in unitary CKM matrix; NP, plenty of places!!!

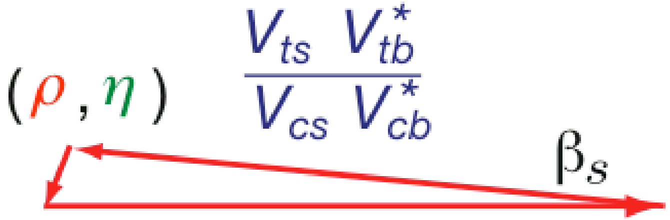
B_s unitarity condition $\quad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$

Golden mode, **Tevatron**



CP violation through interference of diagrams with and w/o mixing

"*Squashed*" *Triangle*



CP Violation in B_s System

- How could New Physics affect these phases

$$2\beta_s^{SM} = 2\arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] \rightarrow \overset{\sim 0.04}{2\beta_s^{SM}} - \phi_s^{NP}$$

$$\phi_s^{SM} = \arg[-M_{12}/\Gamma_{12}] \rightarrow \underset{\sim 0.004}{\phi_s^{SM}} + \phi_s^{NP}$$

Subtracts from one, adds to other

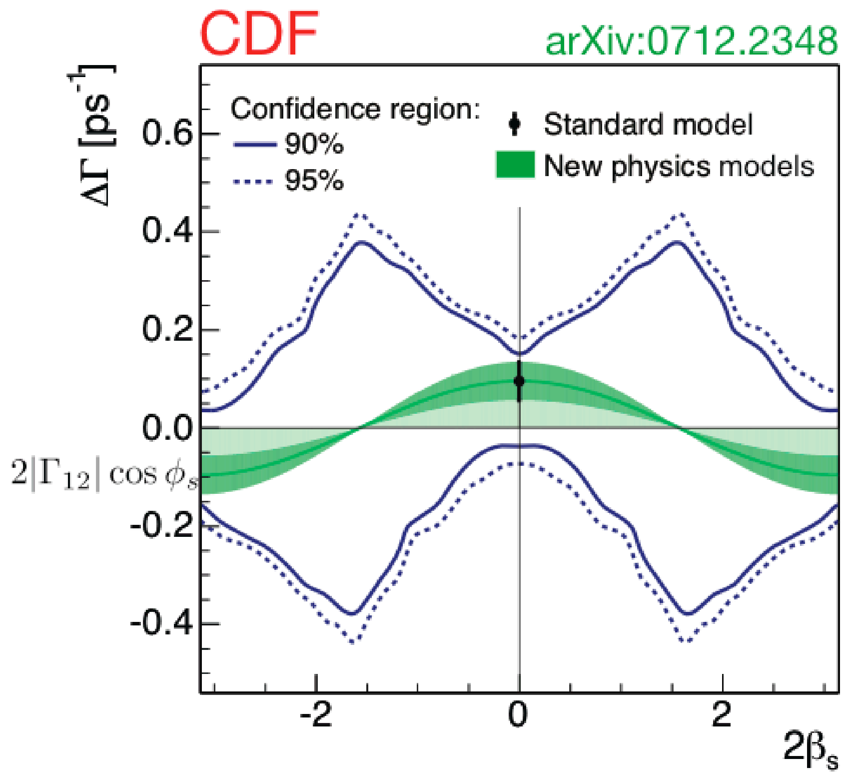
- Both CDF and DØ measure/observe the phase responsible for CP violation in $B_s \rightarrow J/\psi\ \phi$ decays

$$\underset{\text{DØ}}{\phi_s} = \underset{\text{CDF}}{-2\beta_s} \approx \underset{\text{If large}}{\phi_s^{NP}}$$

- Use flavor tagging to identify initial flavor of B_s or Anti B_s in $J/\psi\ \phi$ decays (and know value of Δm_s)

CP Violation in $B_s \to J/\psi\ \phi$

- Even without initial state flavor tagging, have sensitivity to ϕ_s



DØ PRL 98 , 121801 (2007)

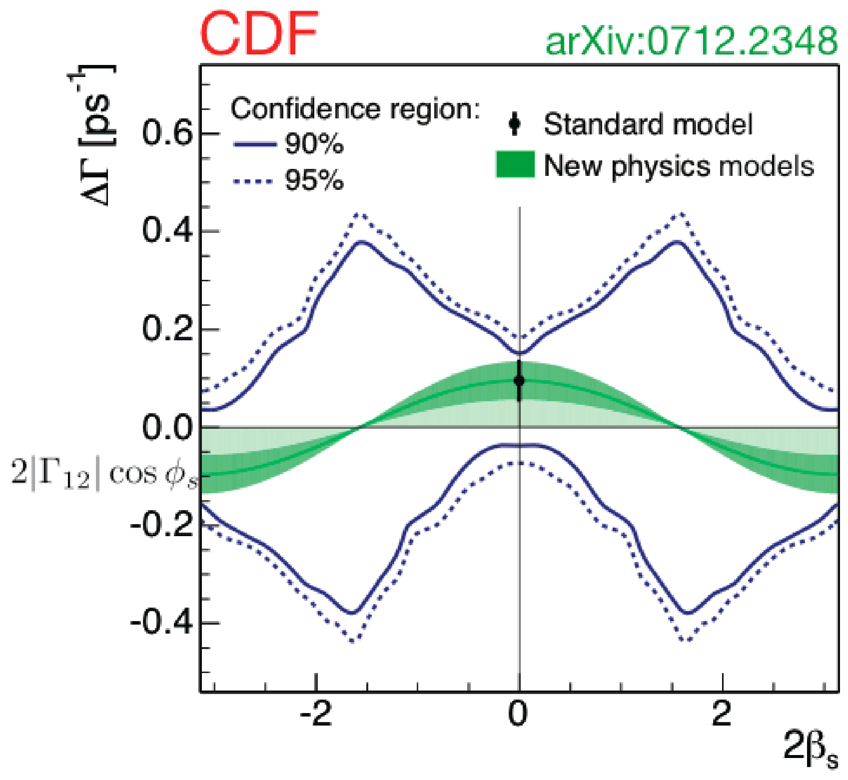
$$\boxed{\phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01}}$$

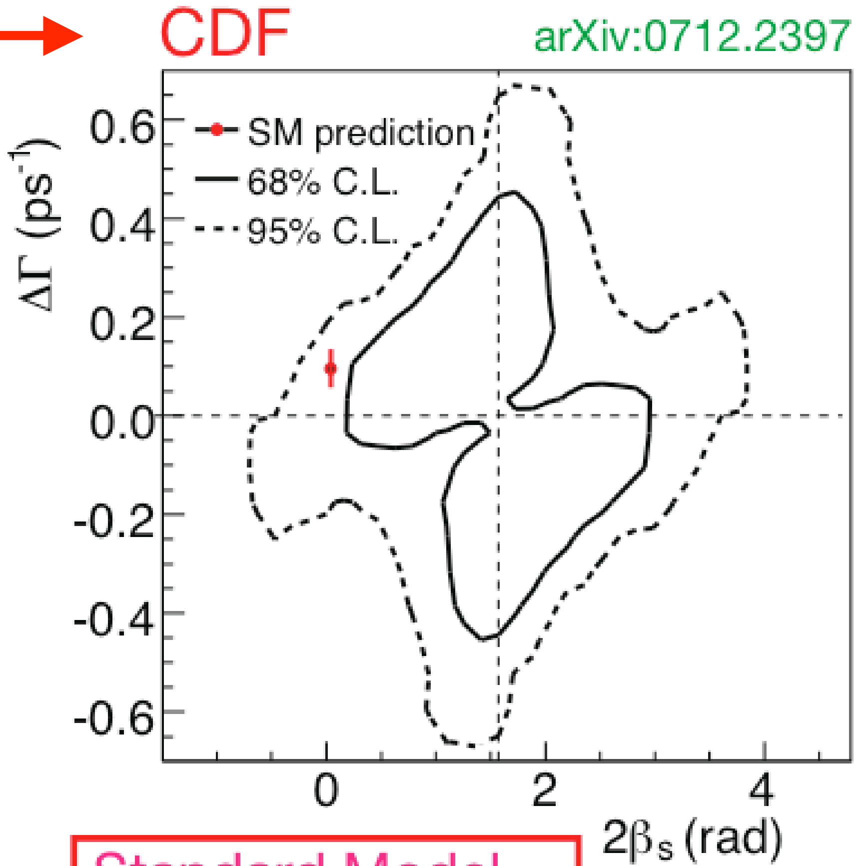
For one of the ambiguities

- But 4-fold ambiguity, reduce to 2-fold

CP Violation in $B_s \to J/\psi\ \phi$

- Now use initial state flavor tagging





Standard Model Probability = 6.6%, ~1.5σ

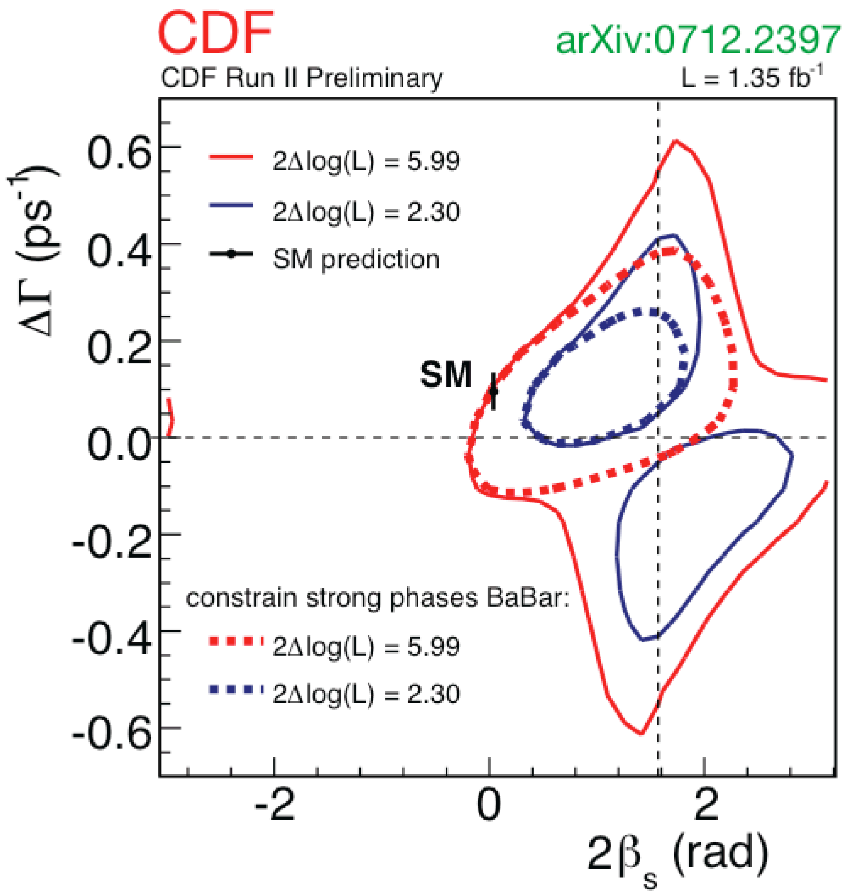
- Ambiguities

Strong phases
(relative phases between polarization amplitudes)

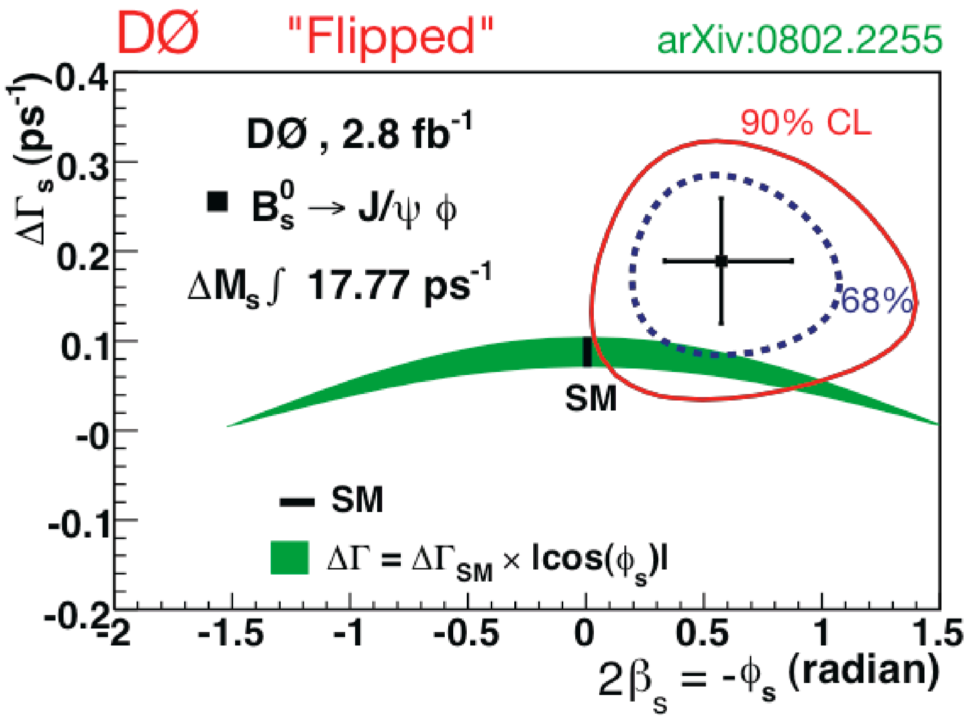
$2\beta_s^{J/\psi\phi} \to \pi - 2\beta_s^{J/\psi\phi} \quad \Delta\Gamma_s \to -\Delta\Gamma_s \quad \delta_{\parallel} \to 2\pi - \delta_{\parallel} \quad \delta_{\perp} \to \pi - \delta_{\perp}$

CP Violation in $B_s \to J/\psi\ \phi$

- Now using initial state flavor tagging, constrain strong phases



Confidence regions underestimated using $2\Delta\log L$



Standard Model Probability = 6.6%, ~1.8σ

- Ambiguities

Constrain based on B_d^0 observations

$$2\beta_s^{J/\psi\phi} \to \pi - 2\beta_s^{J/\psi\phi} \qquad \Delta\Gamma_s \to -\Delta\Gamma_s \qquad \cancel{\delta_\parallel \to 2\pi - \delta_\parallel} \qquad \cancel{\delta_\perp \to \pi - \delta_\perp}$$

ϕ_s Measurement

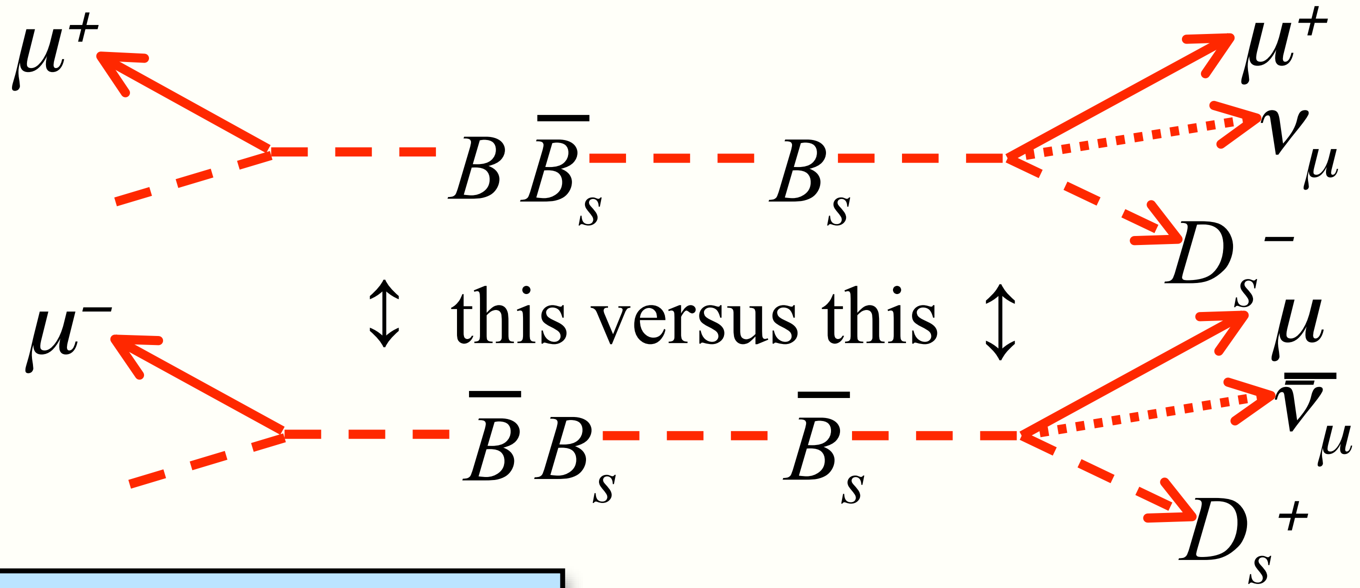
In Standard Model: $\phi_s \approx \arg(-V_{ts}) \approx 0.004$ rad.

Observables: Semileptonic asymmetries, interference in decays to CP eigenstates

<u>Two samples</u>

Exclusive untagged $D_s\mu$

Inclusive like-sign $\mu\mu$



$$\frac{N(D_s\mu^+) - N(D_s\mu^-)}{N(D_s\mu^+) + N(D_s\mu^-)} = A_{SL}(untagged) \approx \frac{\Delta\Gamma}{\Delta m}\tan\phi$$

$$\frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = A_{SL}(tagged) = 2A_{SL}(untagged)$$

Same sign Dimuons

$$\frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = A_{SL}(tagged) = 2A_{SL}(untagged)$$

N(same sign) $\approx$ 310K

$$A_{SL} = -0.0092 \pm 0.0044 \pm 0.0032$$

~60/40 mix of B_d and B_s

$Z \sim 2\chi$

$$A_{SL} = A_{SL}(B_d) + \frac{f_s Z_s}{f_d Z_d} A_{SL}(B_s)$$

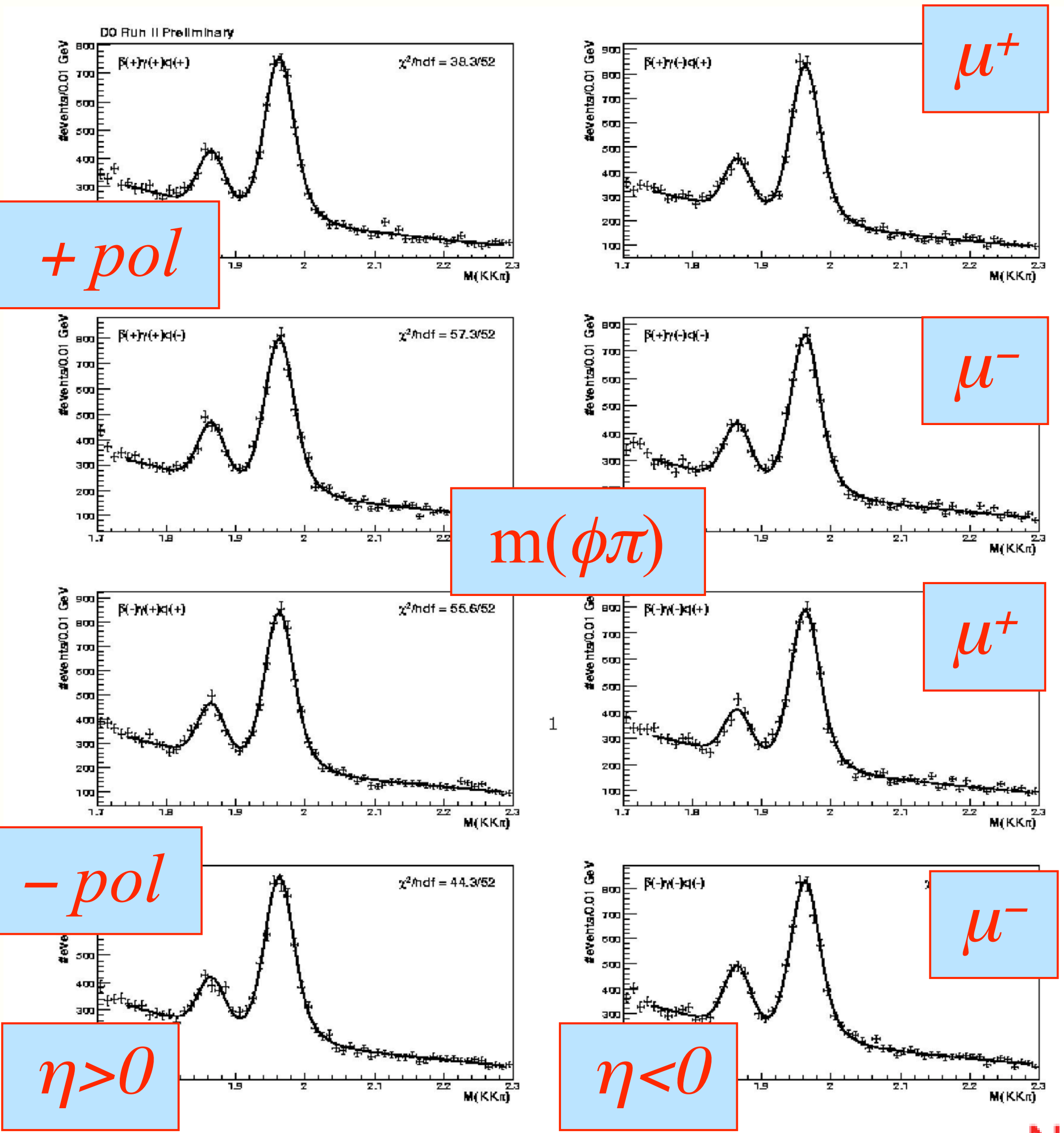
$A_{SL}(B_d)$=-0.0047±0.0046 (HFAG, B-factories)

$$\boxed{A_{SL}(B_s, \mu\mu) = -0.0064 \pm 0.0101}$$

Regular flipping of polarity of solenoid (tracking) and toroid (muons) magnets essential for controlling systematic uncertainties

Exclusive $B_s \to D_s^{\pm}\mu\nu$ Results

Exclusive $D_s\mu$



$$\frac{N(D_s\mu^+) - N(D_s\mu^-)}{N(D_s\mu^+) + N(D_s\mu^-)} = A_{SL}(untagged) \approx \frac{\Delta\Gamma}{\Delta m}\tan\phi$$

$$A_{SL}(B_s, D_s\mu) = 0.0245 \pm 0.0193 \pm 0.0035$$

DØ Combined:

$$A_{SL}(B_s, \mu\mu + D_s\mu) = 0.0001 \pm 0.0090$$

Using Δm_s from CDF:

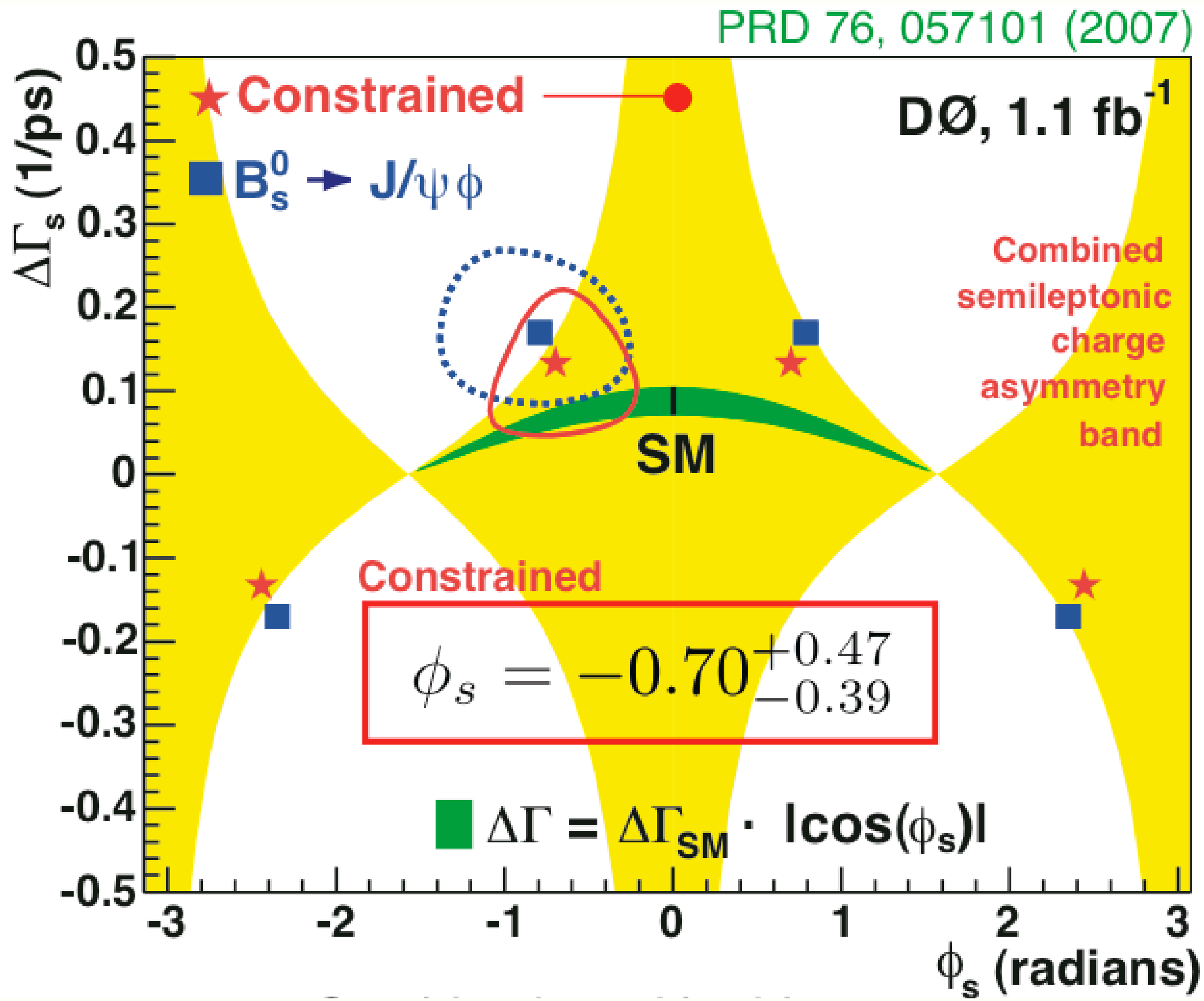
$$\Delta\Gamma_s \cdot \tan\phi_s = 0.02 \pm 0.16\, ps^{-}$$

CDF: 1.6 fb^{-1}, CDF Note 9015

New

$$a^s_{SL} = 0.020 \pm 0.021 \pm 0.018$$

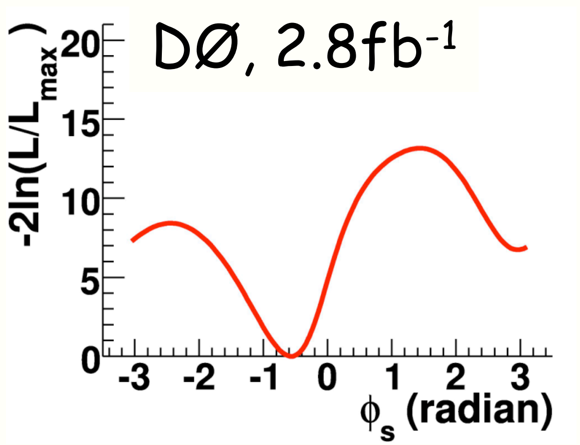
ϕ_s Results



Combined with older DØ analysis before flavor tagging

CP Violation in B_s: Combination

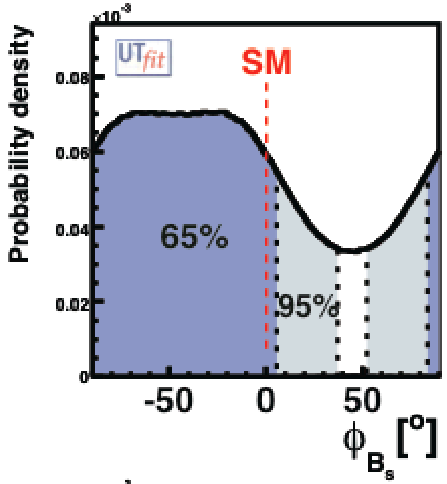
- In $B_s \to J/\psi\ \phi$ flavor-tagged analyses, in $(\Delta\Gamma_s, \phi_s)$ space CDF has ~1.5σ deviation from SM, DØ ~1.8σ deviation, consistent with each other
- Need to be careful, non-parabolic log(L), multiple correlations
  (best is simply more data!!)



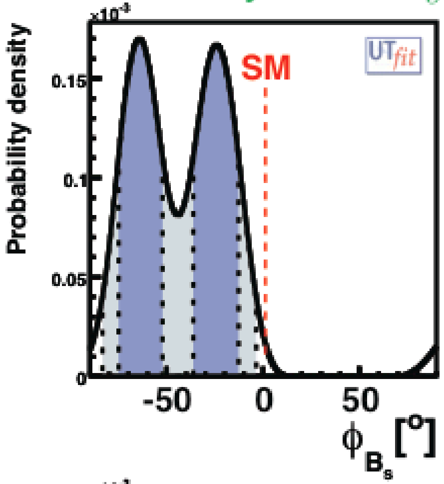
UTfit results

UTfit group, arXiv:0803.0659:

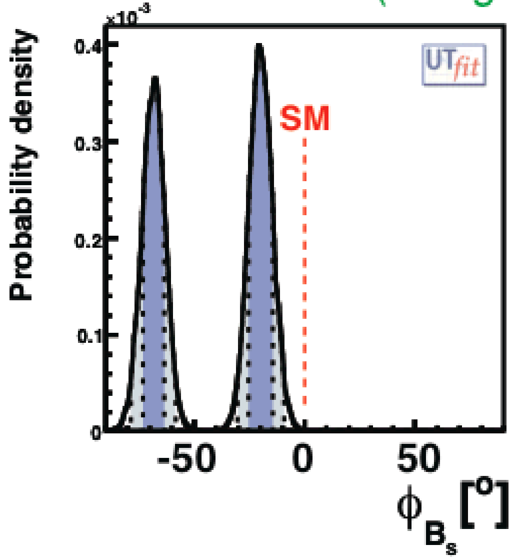
$\Delta m_s,\ A^s_{SL},\ A^{\mu\mu}_{SL},\ \tau_{fs}$

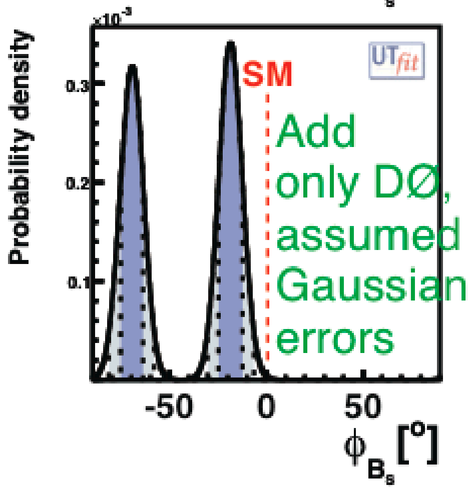


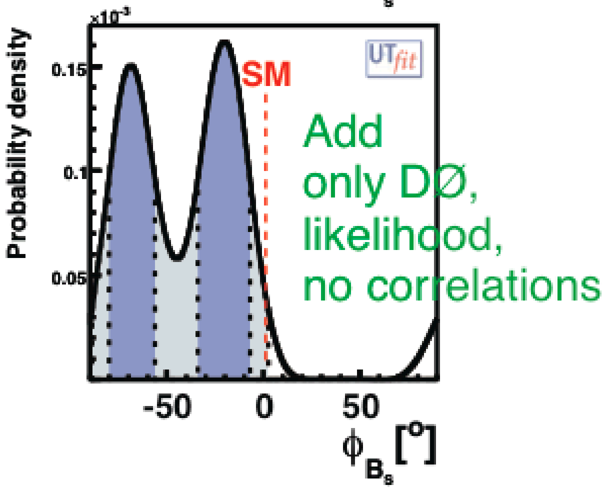
Add only CDF $B^0_s \to J/\psi\phi$



All combined (using DØ Gauss. assumption)







$> 3\sigma$ deviation from SM

- Intriguing, results from DØ, CDF with more data coming soon; CDF+DØ+HFAG also working on combin.

Next talk from Marcella Bona

Direct CP violation in b Hadrons

- Direct (not through mixing) *CP* violation expected to be large in some *b* hadron decays, including *B* mesons and *b Baryons*
- Measure asymmetry: f=final state

$$A_{CP} = \frac{N(\bar{B} \to \bar{f}) - N(B \to f)}{N(\bar{B} \to \bar{f}) + N(B \to f)}$$

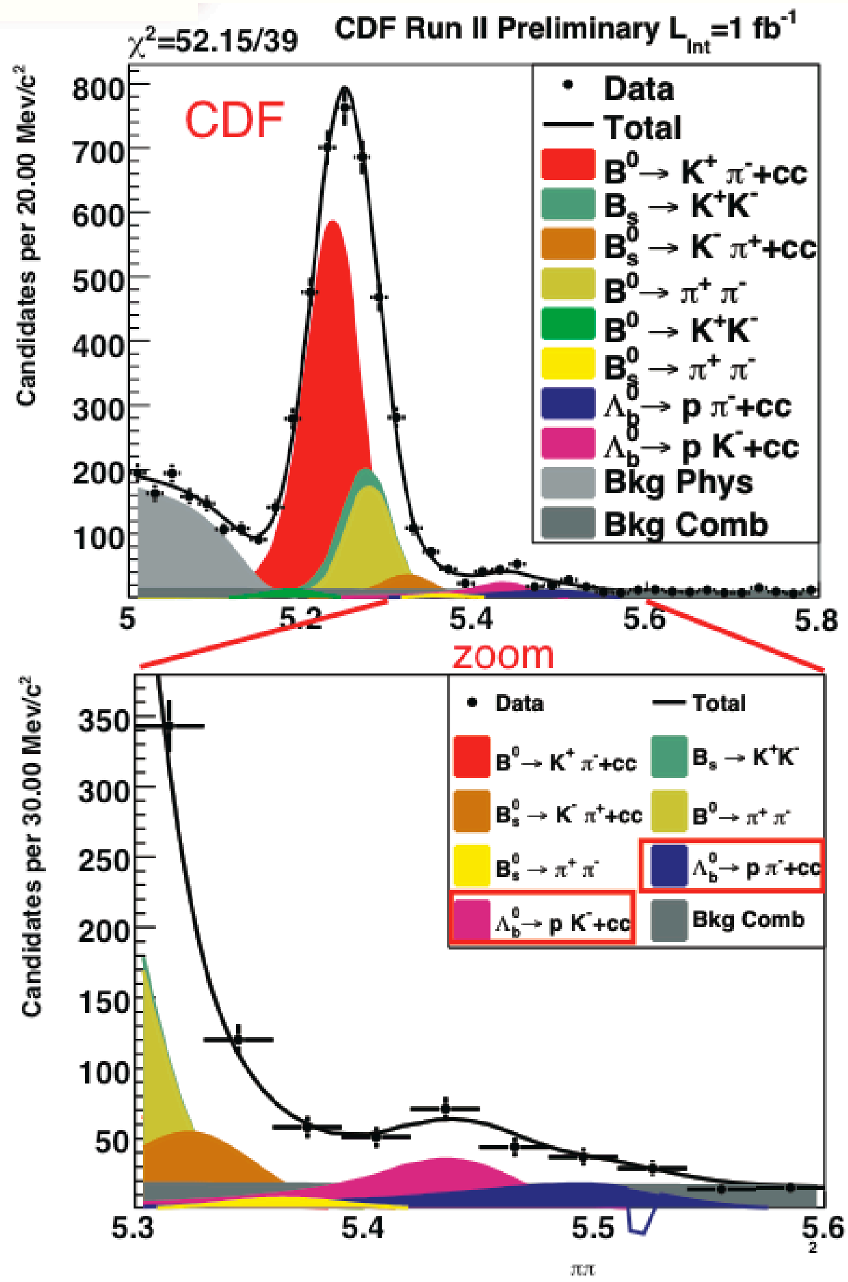
- CDF: *Br*'s and asymmetries of two-body charmless states, B→hh'

CDF Note 9092

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = 0.03 \pm 0.17 \pm 0.05$$

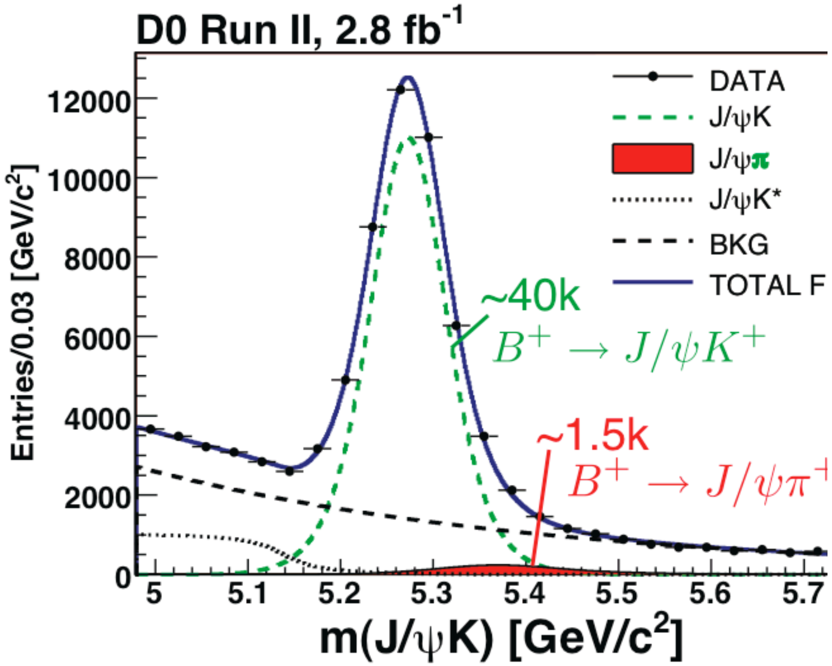
$$A_{CP}(\Lambda_b^0 \to pK^-) = 0.37 \pm 0.17 \pm 0.03$$

- Expectations, asymmetry ~30%
- First *CP* asymmetry measurement in b baryon decays



Direct CP violation in b Hadrons

- DØ: Small (~1%) CP asymmetry expected in SM for $B^+ \to J/\psi K^+$
- Again, frequent solenoid and toroid polarity reversals essential to control charge asymmetry systematic uncertainties
- Correct for K^+/K^- asymmetry
- <1% precision factor ~2 better than current world average

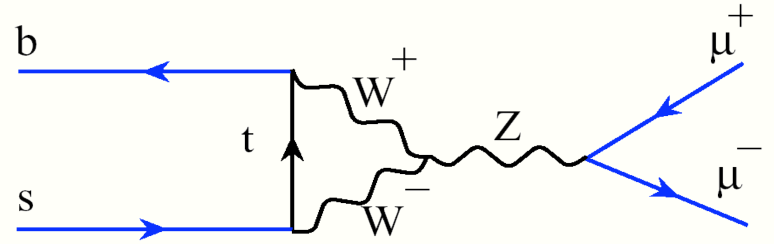


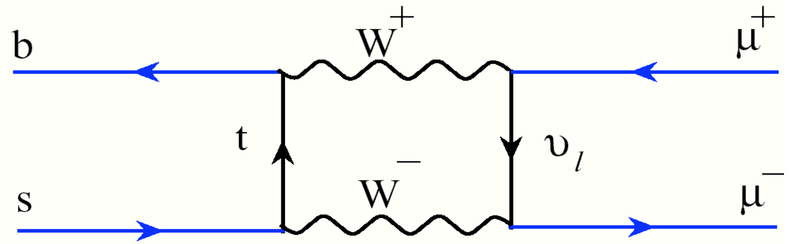
Accepted by Phys. Rev. Lett.
arXiv:0802.3299

$$A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061 \pm 0.0027$$

Purely leptonic B decay

- $B \to l^+ l^-$ decay is helicity suppressed FCNC
- SM: $BR(B_s \to \mu^+\mu^-) \sim 3.4\times10^{-9}$
- depends only on one SM operator in effective Hamiltonian, hadronic uncertainties small
- B_d relative to B_s suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ if no additional sources of flavor violation
- reaching SM sensitivity: present limit for $B_s \to \mu^+\mu^-$ comes closest to SM value





SM expectations:

	$Br(B_d \to l^+l^-)$	$Br(B_s \to l^+l^-)$
$l = e$	3.4×10^{-15}	8.0×10^{-14}
$l=\mu$	1.0×10^{-10}	3.4×10^{-9}
$l=\tau$	3.1×10^{-8}	7.4×10^{-7}

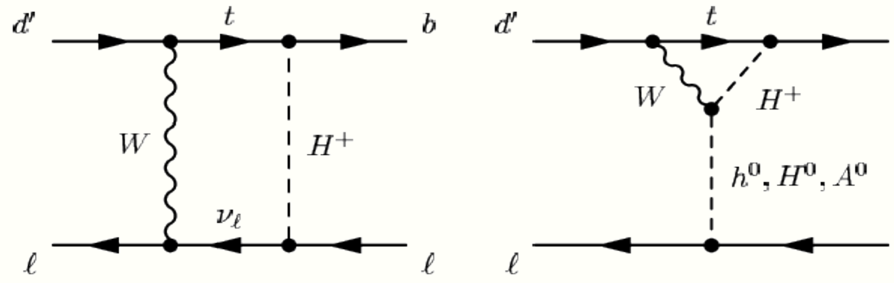
Current published limits at 95%CL:

	$Br(B_d \to l^+l^-)$	$Br(B_s \to l^+l^-)$
$l = e$	$< 6.1 \cdot 10^{-8}$	$< 5.4 \cdot 10^{-5}$
$l=\mu$	$< 1.8 \cdot 10^{-8}$	$<5.8 \times 10^{-8}$
$l=\tau$	< 2.5%	< 5.0%

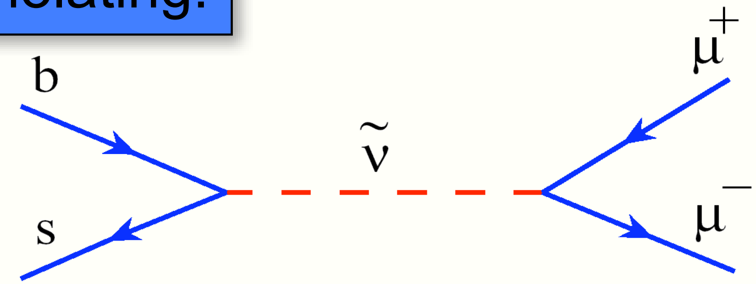
Purely leptonic B decay

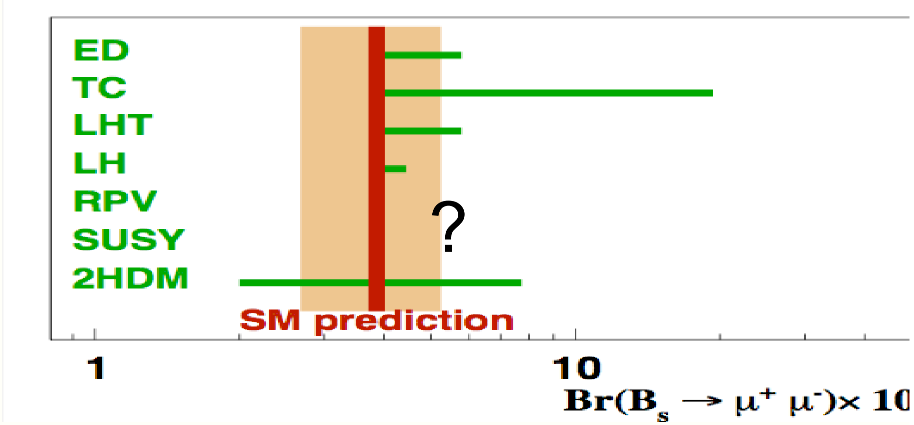
- excellent probe for many new physics models
- particularly sensitive to models w/ extended Higgs sector
  - BR grows ~$\tan^6\beta$ in MSSM
  - 2HDM models ~ $\tan^4\beta$
  - mSUGRA: BR enhancement correlated with shift of $(g-2)_\mu$
- also, testing ground for
  - minimal SO(10) GUT models
  - R_p violating models, contributions at tree level
  - (neutralino) dark matter …

Two-Higgs Doublet models:



R_p violating:

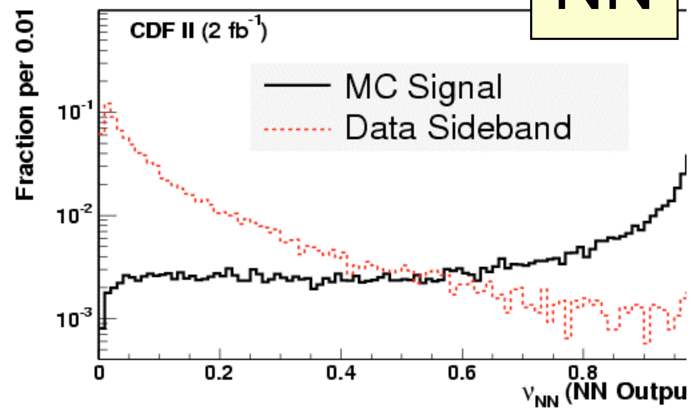


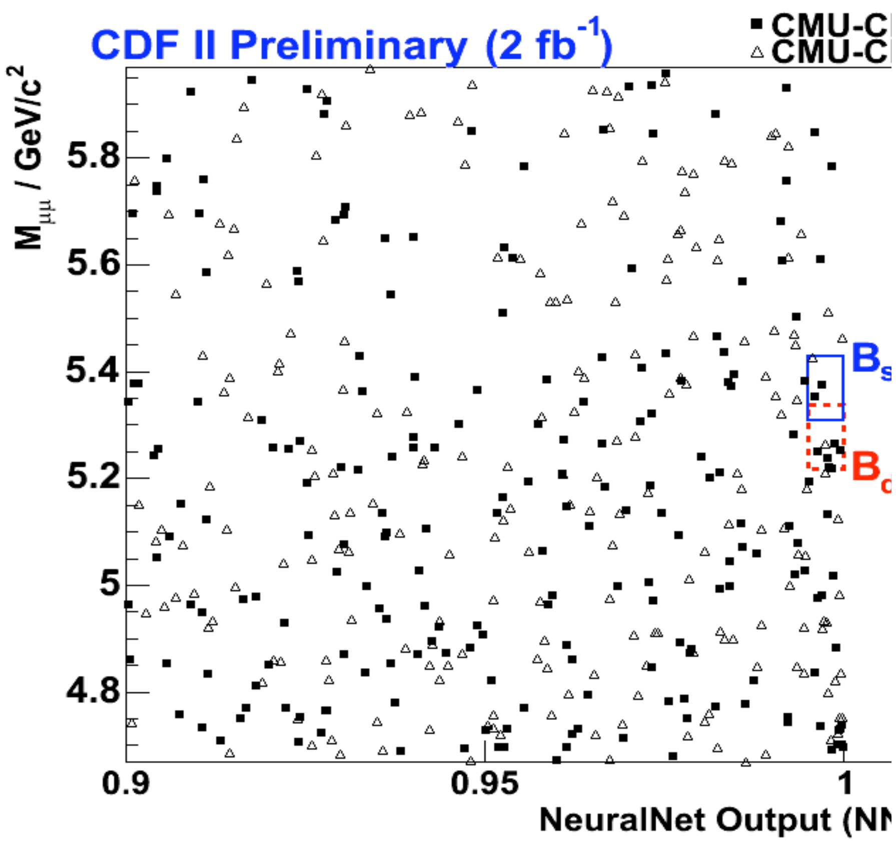


Search Strategy

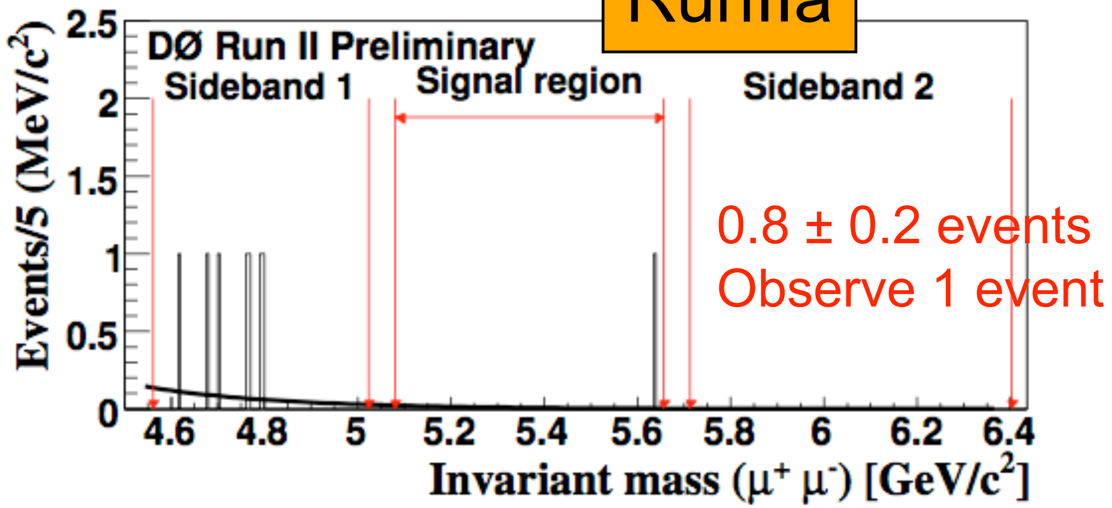
- Preselection of Di Muon events
- Normalization channel $B^+ \rightarrow J/\psi K^+$
- Background estimation using sidebands
- Background reduction using a LHR (DØ) or NN (CDF)

NN





RunIIa



Limits

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < \frac{N_{UL}}{\boxed{N_{B^+}}} \cdot \boxed{\frac{\varepsilon^{B^+}_{\mu^+\mu^- K}}{\varepsilon^{B_s^0}_{\mu^+\mu^-}}} \cdot \frac{\mathcal{B}(B^\pm \to J/\psi(\mu^+\mu^-)K^\pm)}{\boxed{\frac{f_{b\to B_s}}{f_{b\to B_{u,d}}}} + \boxed{R \cdot \frac{\epsilon^{B_d^0}_{\mu^+\mu^-}}{\epsilon^{B_s^0}_{\mu^+\mu^-}}}}$$

Relative Normalization

$\varepsilon_{B^+} / \varepsilon_{Bs}$ relative efficiency of normalization to signal channel

f_s/f_u fragmentation ratio - use world average (3.71) with 15% uncertainty

$\varepsilon_{Bd} / \varepsilon_{Bs}$ relative efficiency for $B_d \to \mu^+ \mu^-$ versus $B_s \to \mu^+ \mu^-$ events in B_s search channel (~0.95) R = BR(B_d)/BR(B_s) is small due to $|V_{td}/V_{ts}|^2$

at 90% C

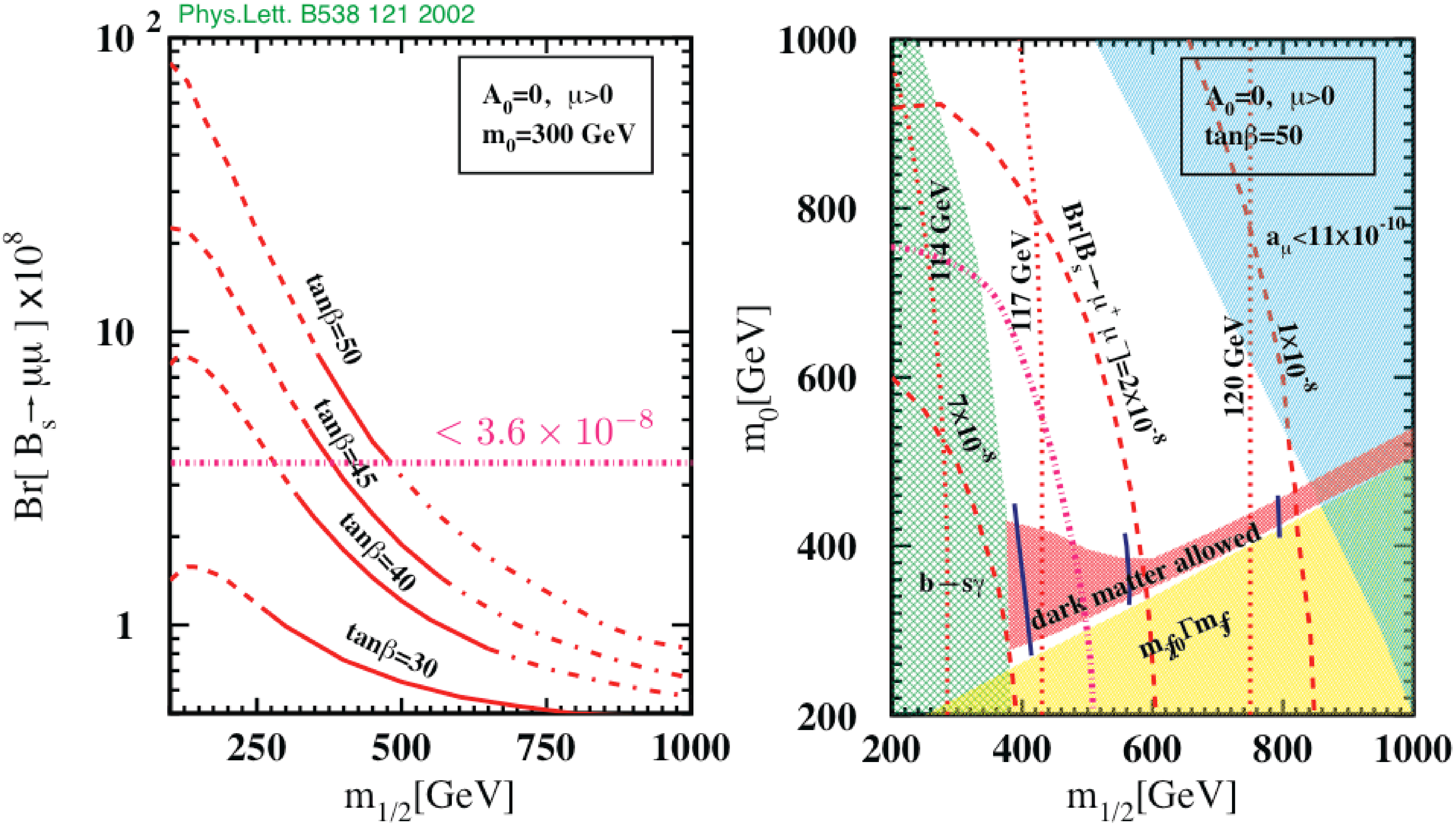
Br($B_s \to \mu\mu$)	2 fb^{-1}	7.3×10^{-8}	Prelim.DØ
Br($B_s \to \mu\mu$)	2 fb^{-1}	4.7×10^{-7}	Prelim.CDF
Br($B_s \to \mu\mu$)	combined	3.6×10^{-8}	HFAG

DØ Note 5344

PRL 100,101802 (2

Rare decays constraining NP

Phys.Lett. B538 121 2002

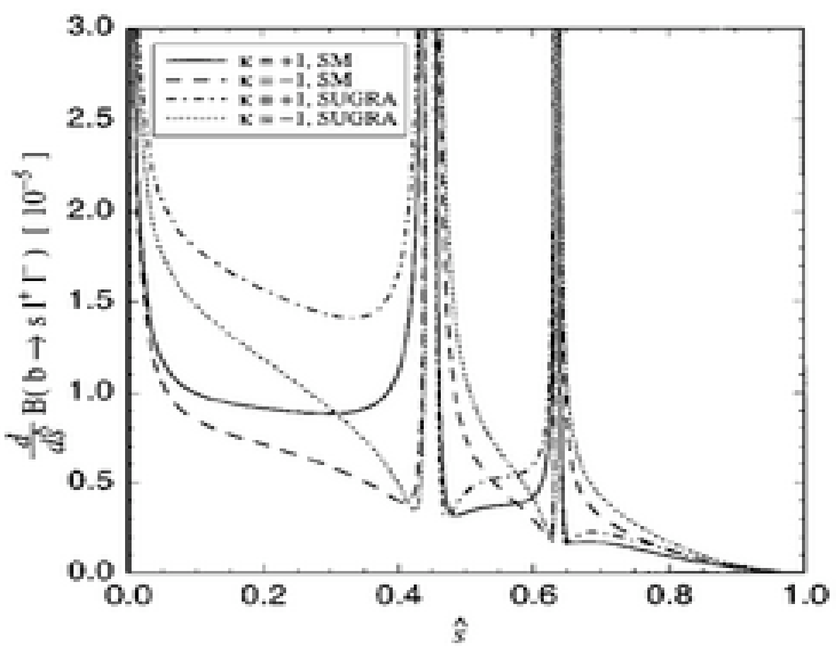


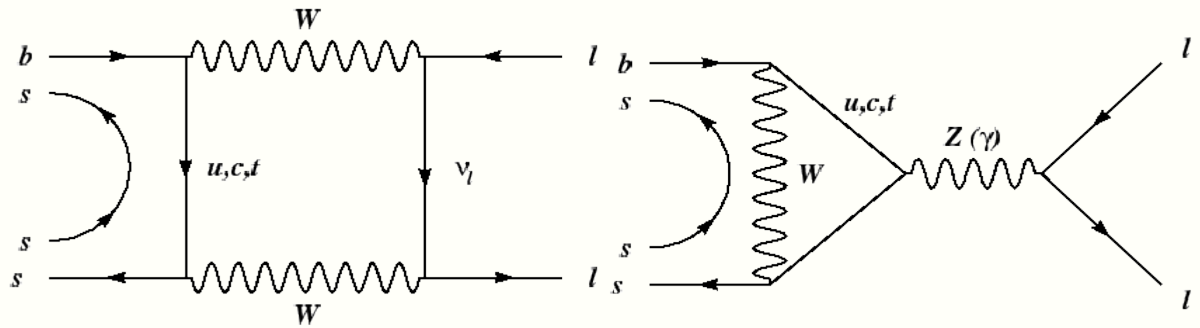
Study of b -> s l^+l^-

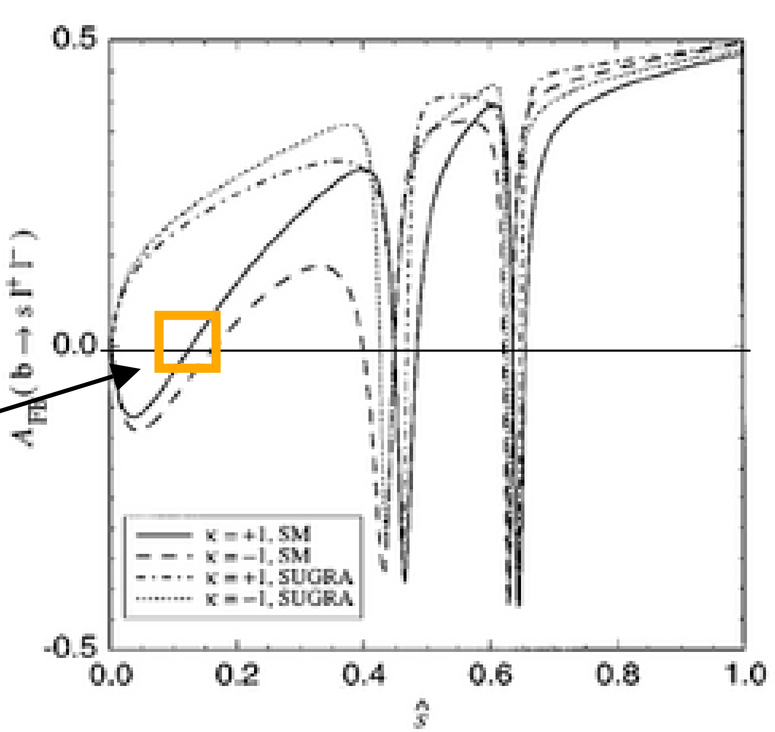
- long-term goal: investigate b -> s l^+ l^- FCNC transitions in B^+, B_d and B_s mesons
- B^+ -> l^+ l^- K^+ and B_d -> l^+ l^- K^* established at B factories
- B_s -> l^+ l^- ϕ only accessible at the Tevatron
  - SM prediction:
    - short distance BR: ~1.6×10^{-6}
    - About 30% uncertainty due to B->ϕ form factor
- 2HDM: enhancement possible, depending on parameters for $\tan\beta$ and M_{H+}

b->sl⁺l⁻ Theory

μμ Mass spectrum





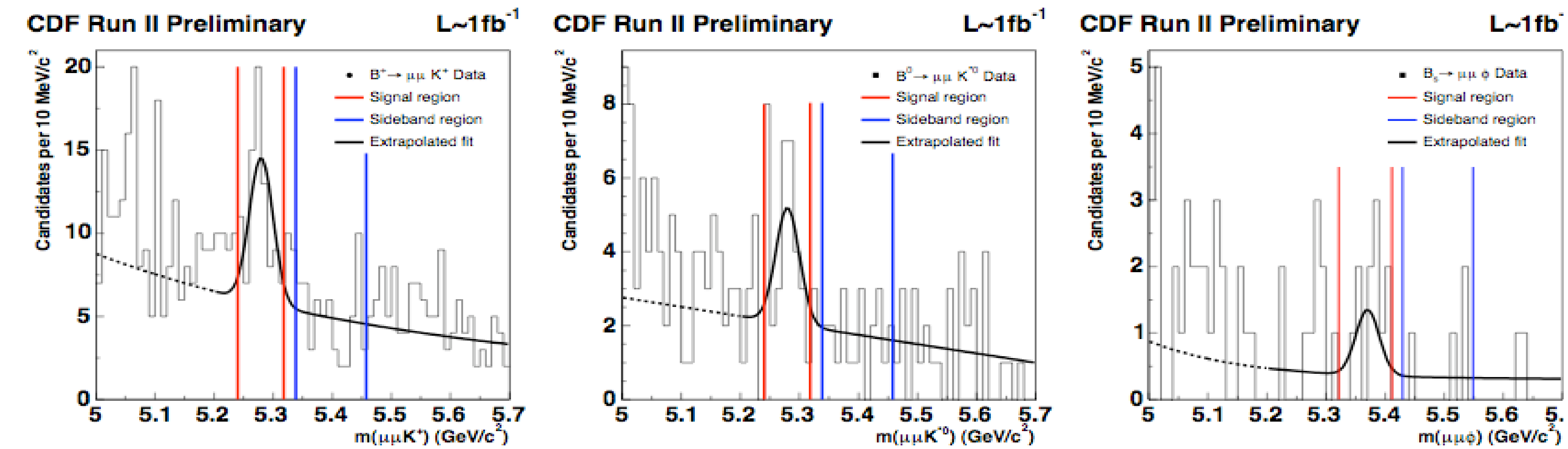


Sensitive to "new Physics" contribution

The forward backward asymmet is defined as the asymmetry betwee forward and backward emitted positive leptons ir the dilepton rest frame where the direction is relative the direction of the meson.

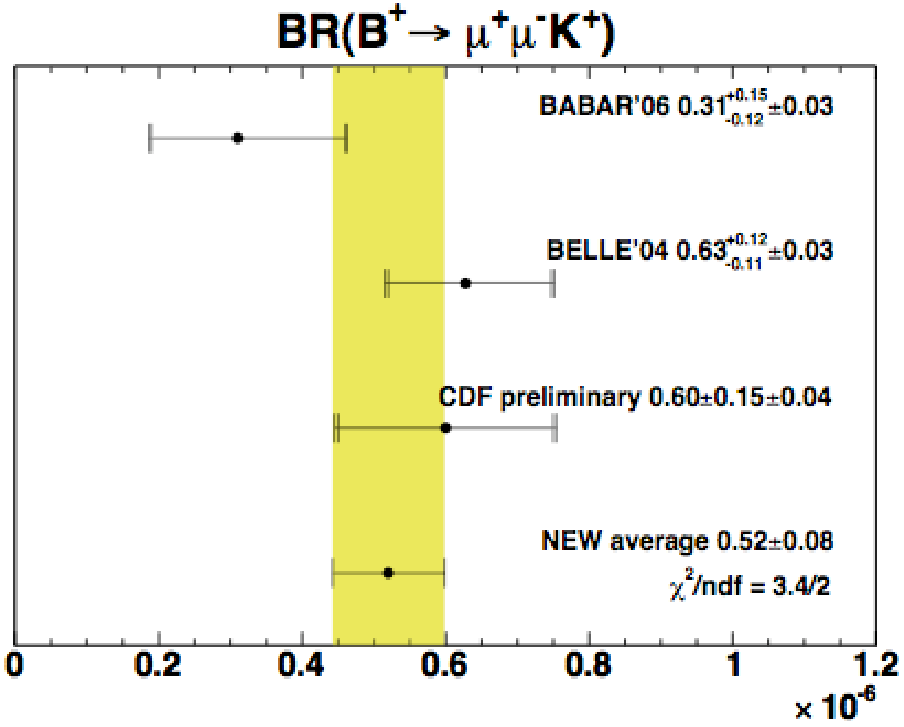
B->μμh @ CDF

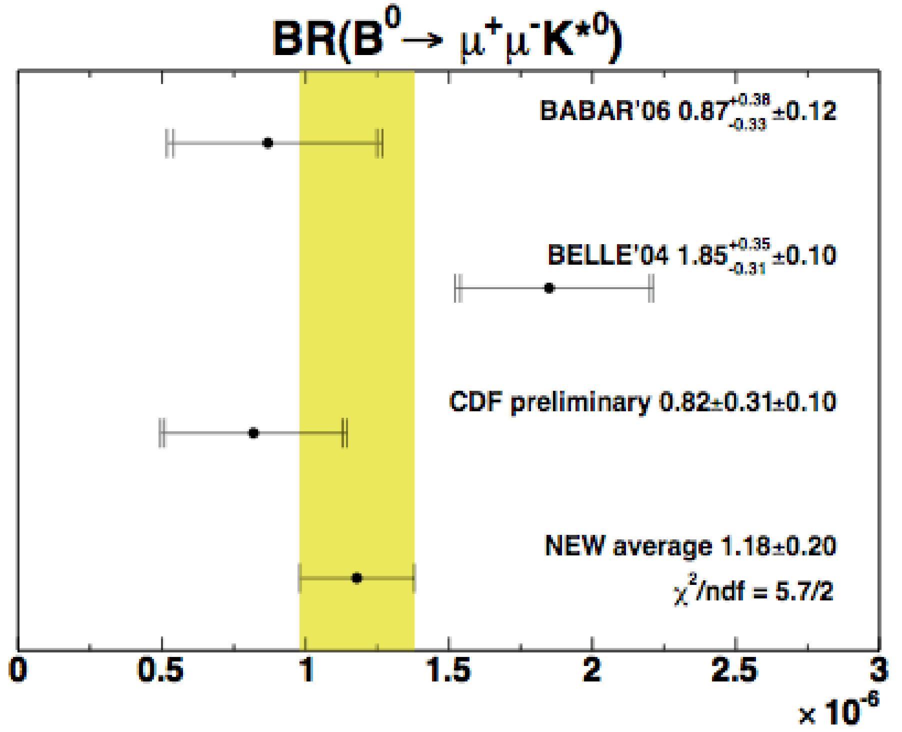
arXiv:0804.3908



Mode	$B^+ \to \mu^+\mu^- K^+$	$B_d^0 \to \mu^+\mu^- K^{*0}$	$B_s^0 \to \mu^+\mu^- \phi$
N_S	90	35	11
N_{BG}	45.3 ± 5.8	16.5 ± 3.6	3.5 ± 1.5
Gaussian significance	4.5	2.9	2.4
$N_{J/\psi h}$	6246 ± 79	2346 ± 48	421 ± 21
$\epsilon_{\mu^+\mu^- h}/\epsilon_{J/\psi h}$	0.71 ± 0.01	0.74 ± 0.02	0.84 ± 0.02
Rel $\mathcal{B} \pm stat \pm syst \times 10^{-3}$	$0.59 \pm 0.15 \pm 0.03$	$0.62 \pm 0.23 \pm 0.07$	$1.24 \pm 0.60 \pm 0.15$
Abs $\mathcal{B} \pm stat \pm syst \times 10^{-6}$	$0.60 \pm 0.15 \pm 0.04$	$0.82 \pm 0.31 \pm 0.10$	$1.16 \pm 0.56 \pm 0.42$
Rel $\mathcal{B}$ 95%CL limit $\times 10^{-3}$	—	—	2.61
Rel $\mathcal{B}$ 90%CL limit $\times 10^{-3}$			2.30

Branching ratio overview





Need more statistics to measure charge asymmetry vs. invariant di-lepton mass and to add Bs channel!

Summary

- Δm_s established and well measured at the Tevatron
- B_s system and CP studies opening a powerful new window: possibly already providing hints of new phenomena?
- Limit on rare decay $B_s \to \mu^+\mu^-$ is getting more and more stringent, help constrain physics beyond the SM
- Other FCNC (b-> sll) decays test the SM
- Tevatron doing very well, expect to at least *double* our data-set by the end of running

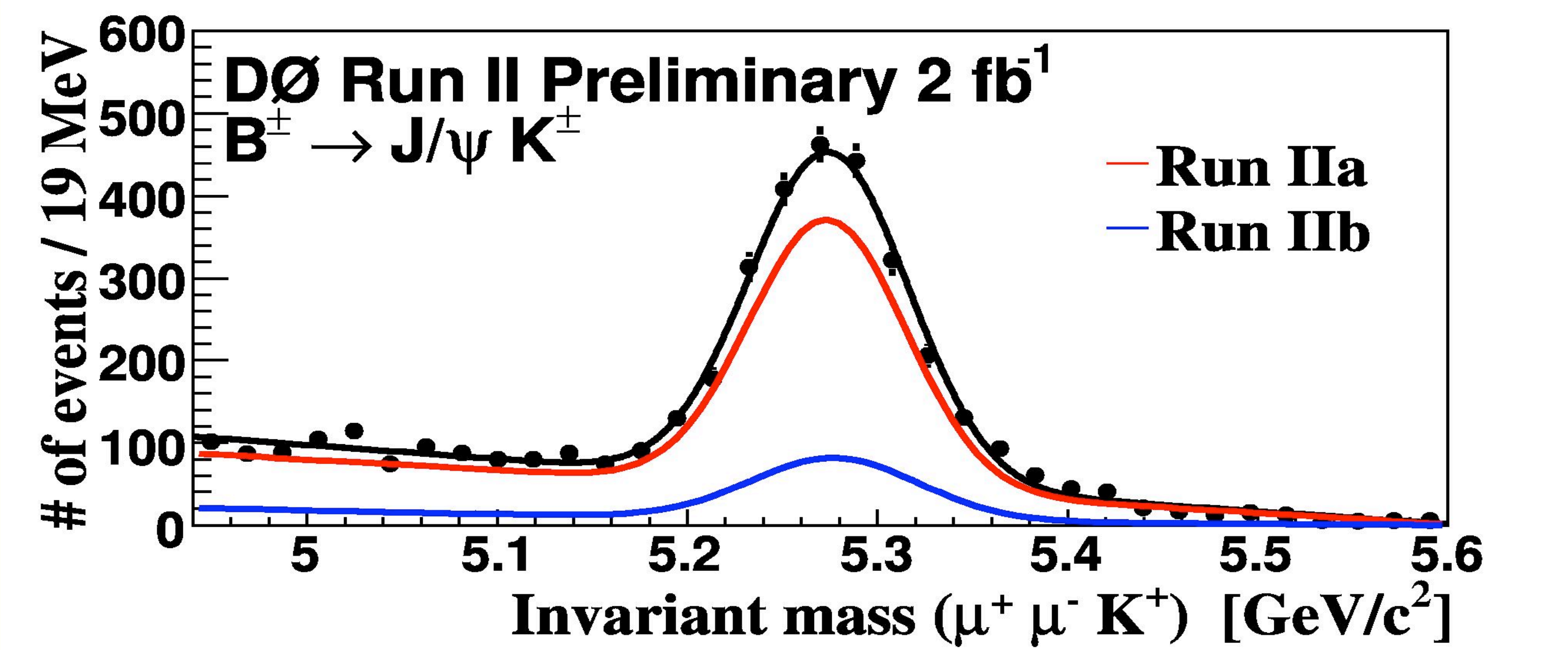
Back up slides

Pre-Selection

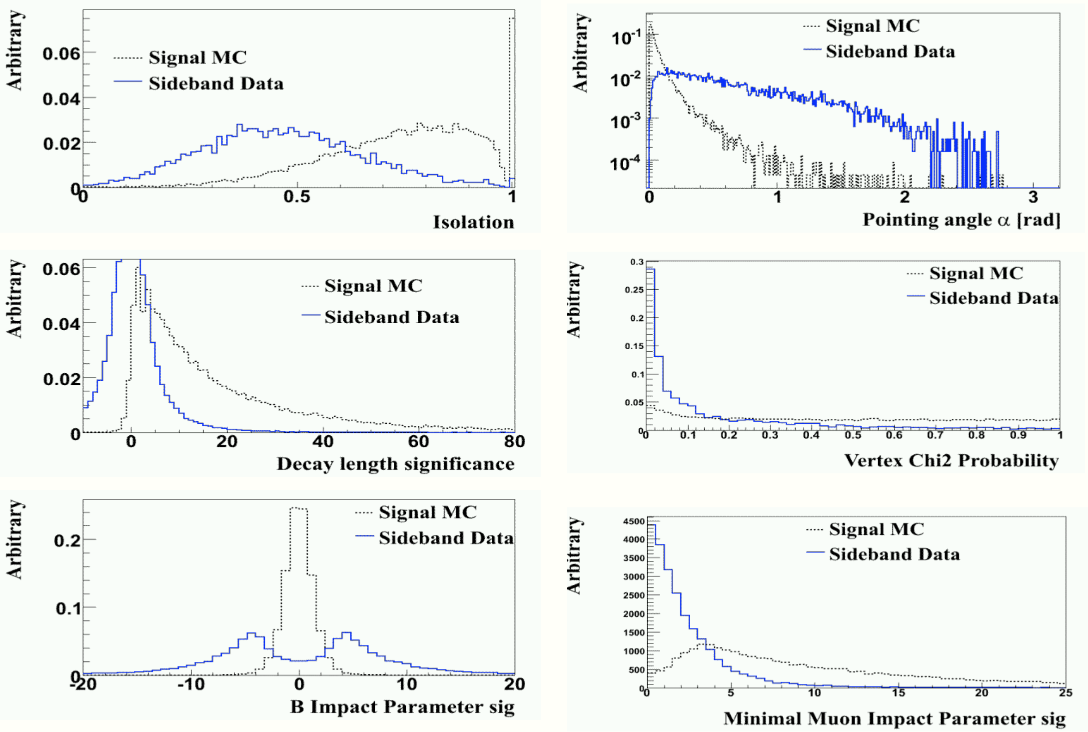
- Cut on Mass region of di-muon sample $4.5 < m_{\mu\mu} < 7$ GeV/c2
- Two medium muons with a net charge of zero and a p_T greater than 2.5 GeV
- The triggered muons have reconstructed tracks in the tracker with
  - at least 3 hits in the Silicon tracker
  - at least 4 hits in the Fiber tracker
- Good reconstructed vertex (χ^2 cut)
- Cut on the uncertainty of the transverse decay length $\sigma(Lxy) < 150\ \mu m$
- A minimum pT of the Bs candidate of 5 GeV is required

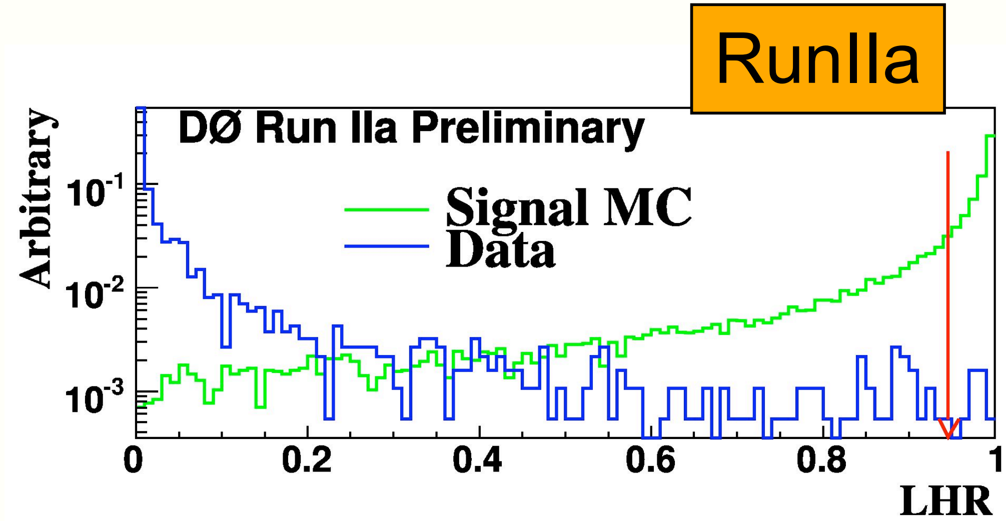
Normalization

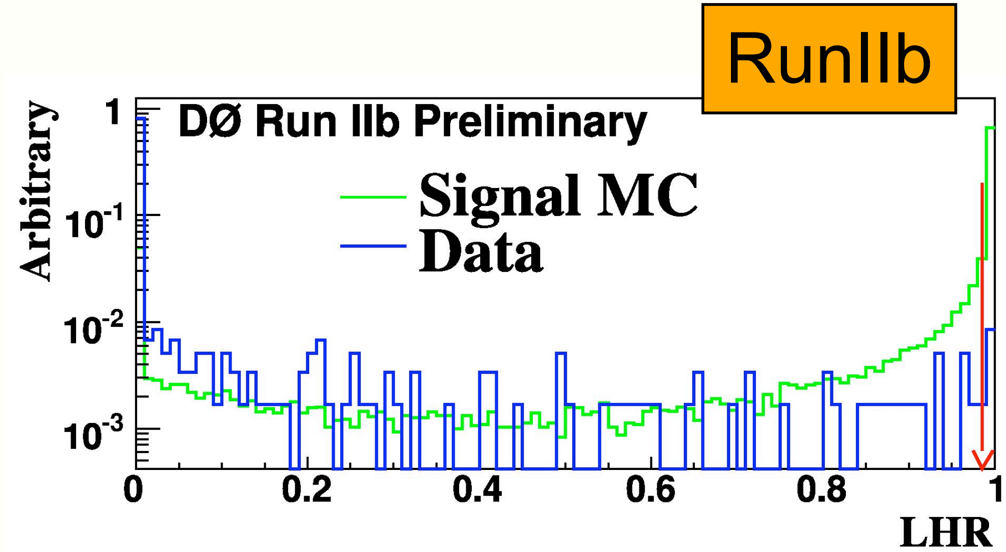
- Additional cuts on the Kaon and B candidate are:
  - Kaon $p_T > 0.9$ GeV/c
  - Collinearity of > 0.9 is required
  - χ^2 of the vertex fit contribution not more than 10, together < 20
  - Also cut on the LHR cut like the $B_s \to \mu^+\mu^-$ signal



Likelihood







$$LHR = \frac{\prod_{i=0}^{6} s_i(x)}{\prod_{i=0}^{6} s_i(x) + \prod_{i=0}^{6} b_i(x)}$$

Systematic Uncertainties

Source	Relative Uncertainty [%]	
	RunIIa	RunIIb
$\epsilon^{B^\pm}_{\mu\mu K} / \epsilon^{B^0_s}_{\mu\mu}$	6.7	9.0
# of $B^\pm \to J/\psi K^\pm$	3.2	5.7
$\mathcal{B}(B^\pm \to J/\psi K^\pm)$	4.0	4.0
$\mathcal{B}(J/\psi \to \mu\mu)$	1.7	1.7
$f_{b\to B^0_s} / f_{b\to B^\pm}$	12.7	12.7
background uncertainty	25	33

$B_s \to J/\psi\ \phi$

Time evolution: pure even case

$$\boxed{\begin{array}{l}\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 \\ f(t,even) \approx e^{-\Gamma_L t}\end{array}}$$

Time evolution: even plus odd components

$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

$$+ A^* A(CPC)$$

CP conserving interference

$$f(t,even) \approx e^{-\Gamma_L t}$$

$$f(t,odd) \approx e^{-\Gamma_H t}$$

CP states = heavy, light states

$B_s \to J/\psi\ \phi$

Time dependent angular analysis of untagged sample

Time evolution: even plus odd plus CPV

$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

$$+ A^* A(CPC)$$

CP conserving interference

$$+ A^* A(CPV)(e^{-\Gamma_L t} - e^{-\Gamma_H t})\sin\phi_s$$

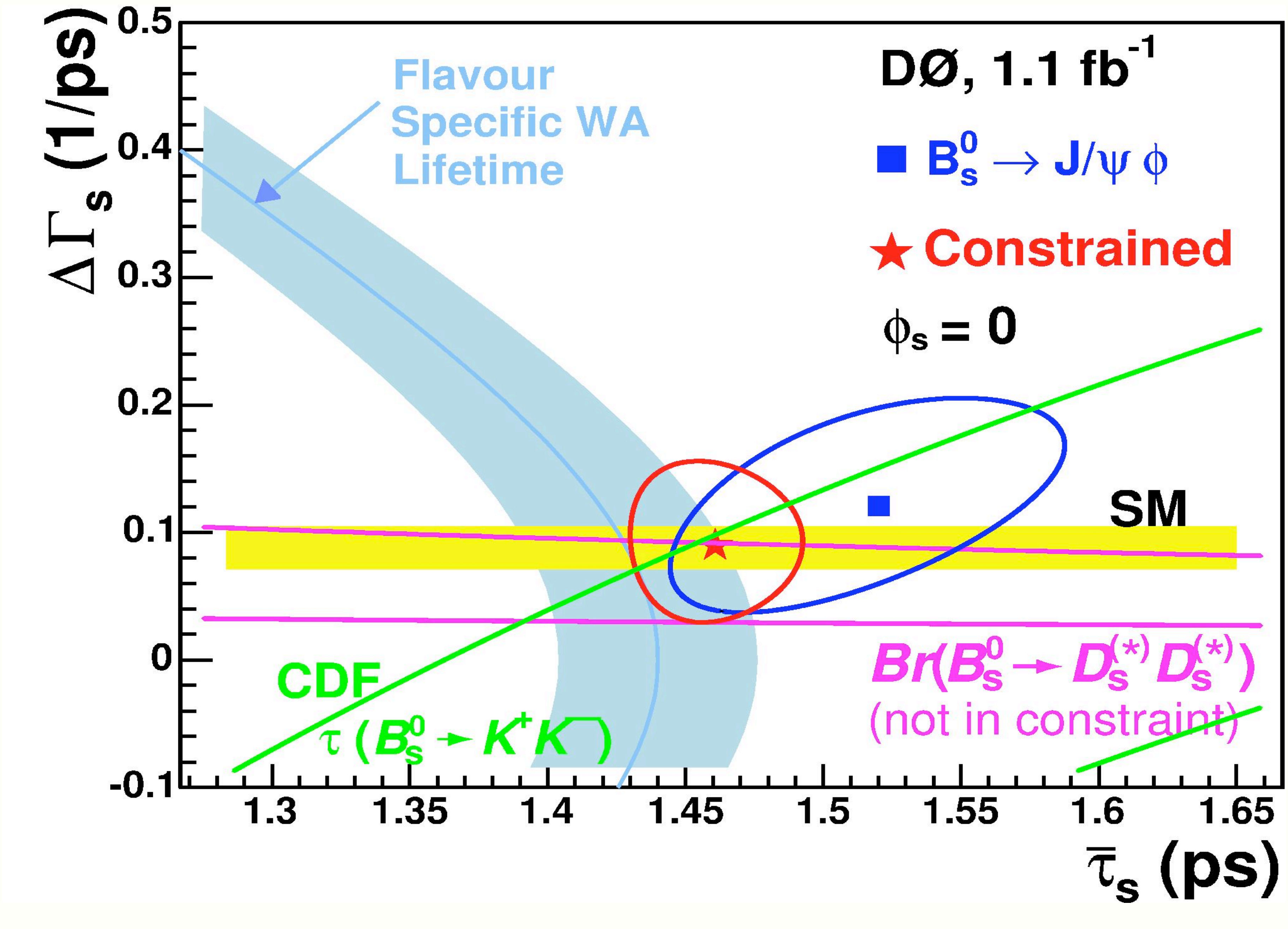
CP violating interference between two paths

$$f(t,even) \approx (1+\cos\phi_s)e^{-\Gamma_L t} + (1-\cos\phi_s)e^{-\Gamma_H t}$$

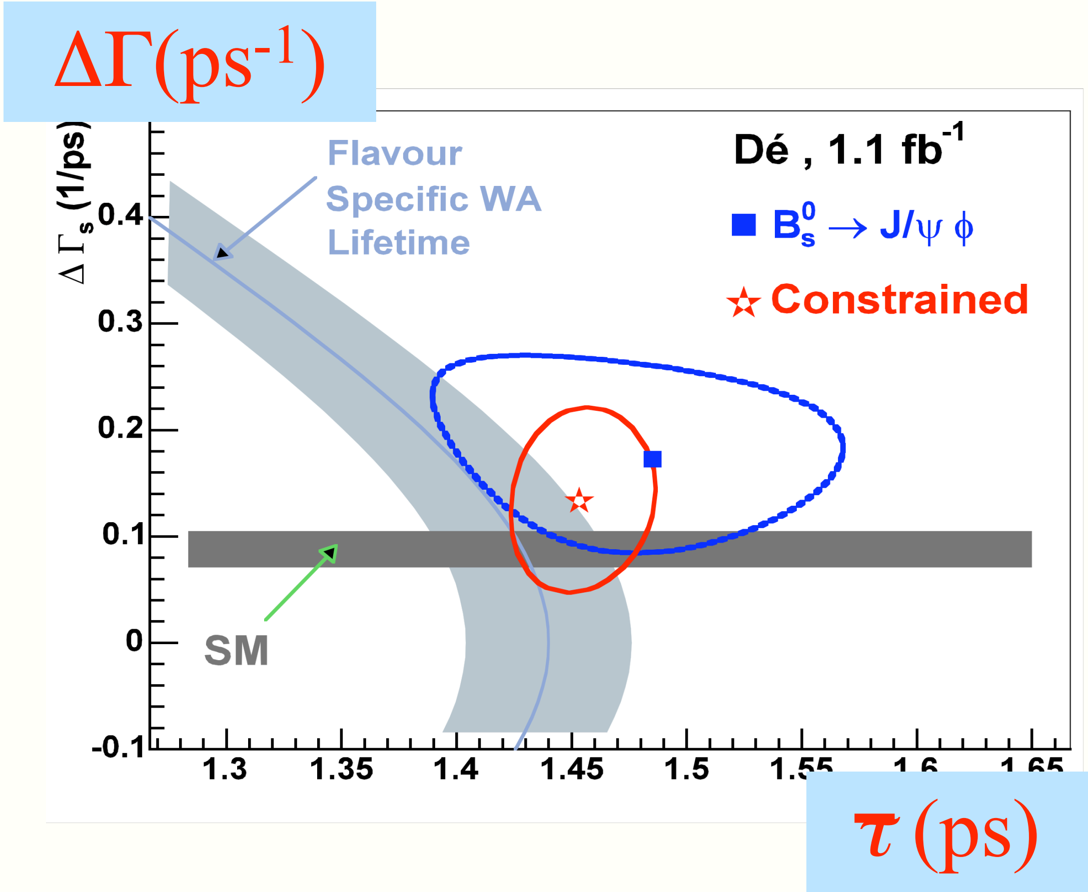
$$f(t,odd) \approx (1+\cos\phi_s)e^{-\Gamma_H t} + (1-\cos\phi_s)e^{-\Gamma_L t}$$

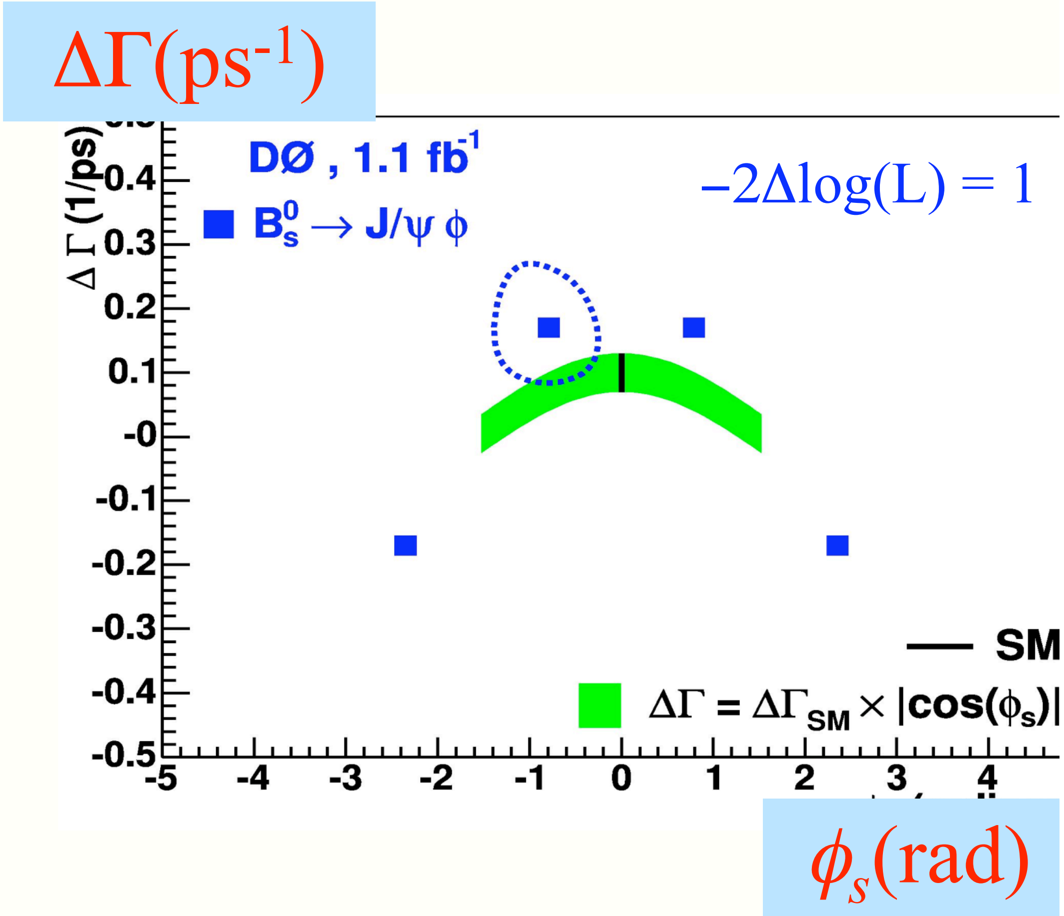
Heavy and light states are mixed CP

Combined $\Delta\Gamma$ ($\cos\phi_s \equiv 1$)



$B_s \to J/\psi\, \phi$ Results



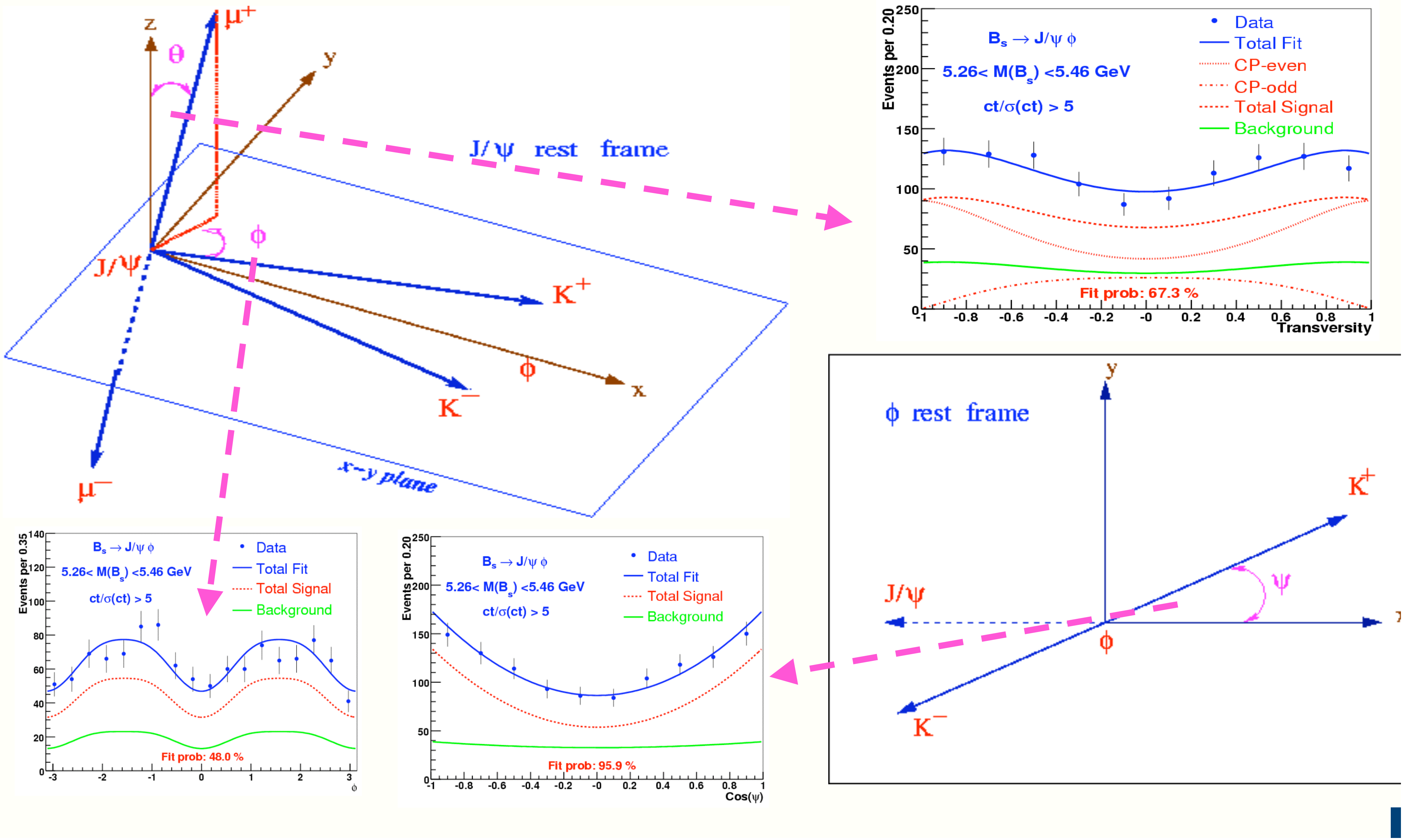


Likelihood invariant to simultaneous flip of sign of ΔΓ and even-odd strong phase difference ⇒ 4-fold ambiguity

$$\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.02\, ps^{-1}$$

$$\phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01}$$

$B_s \to J/\psi\ \phi$ angles



Flavor Specific B_s Lifetime

Flavor specific decays carry equal amounts of B_H and B_L

$$\left|B_s \to D_s \mu \nu\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_H\right\rangle + \left|B_L\right\rangle\right)$$

$$e^{-t/\tau_{FS}} \equiv \frac{1}{2}\left(e^{-t/\tau_H} + e^{-t/\tau_L}\right)$$

Get the flavor specific lifetime when you fit FS data with single exponential

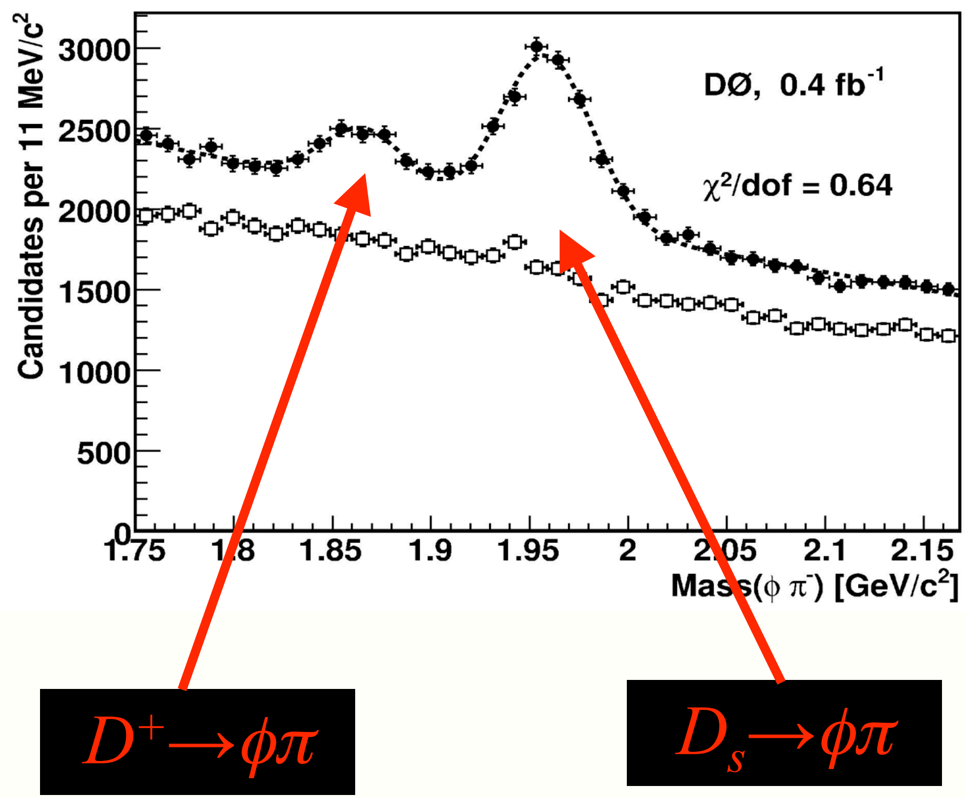
$$\tau_{FS} = \frac{1}{\overline{\Gamma}_s}\left(\frac{1+y^2}{1-y^2}\right)$$

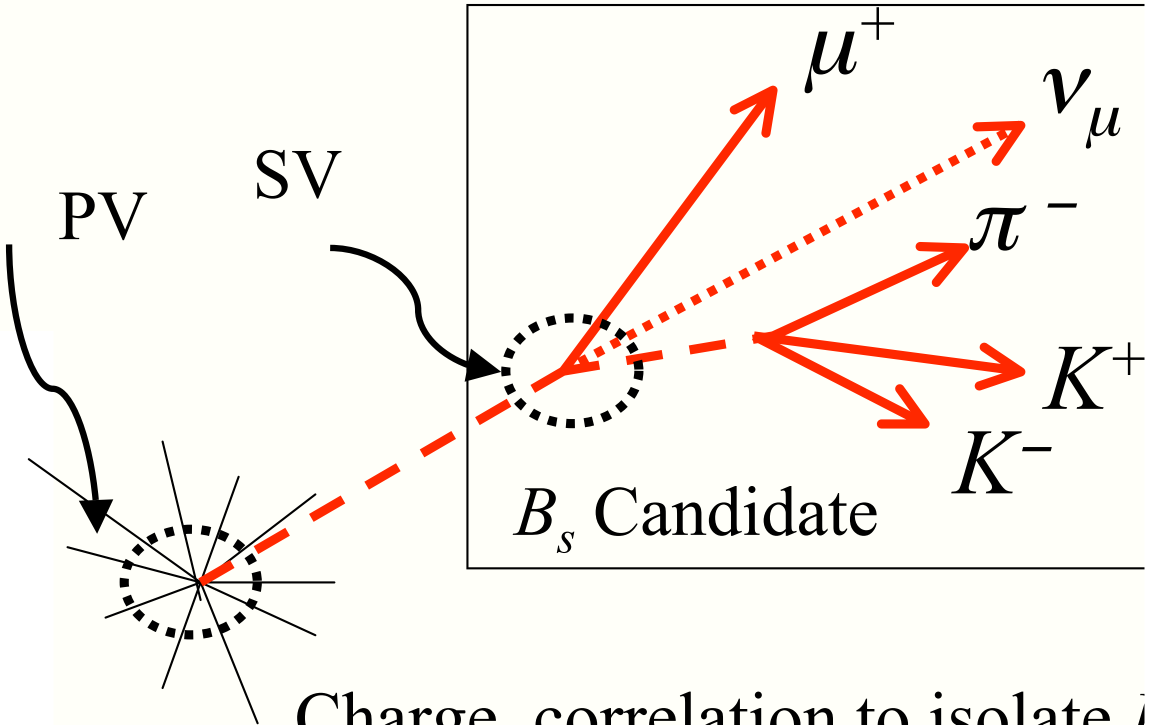
Maps out a 2-D constraint on the average width and the width difference

$$y = \frac{\Delta\Gamma}{2\Gamma}$$

hep-ph/0201071

B_s Semileptonic Sample





Charge correlation to isolate B_s sample

Transverse decay length determined in lab frame

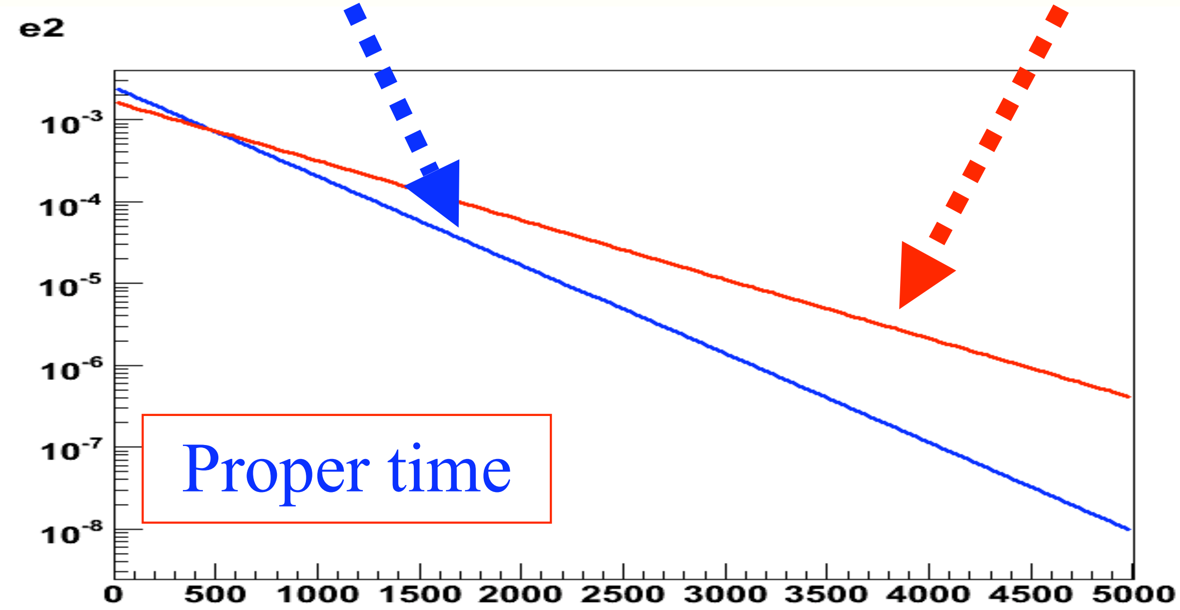
Boost back using MC to estimate neutrino momentum

$B_s \to J/\psi\ \phi$: $P \to VV$

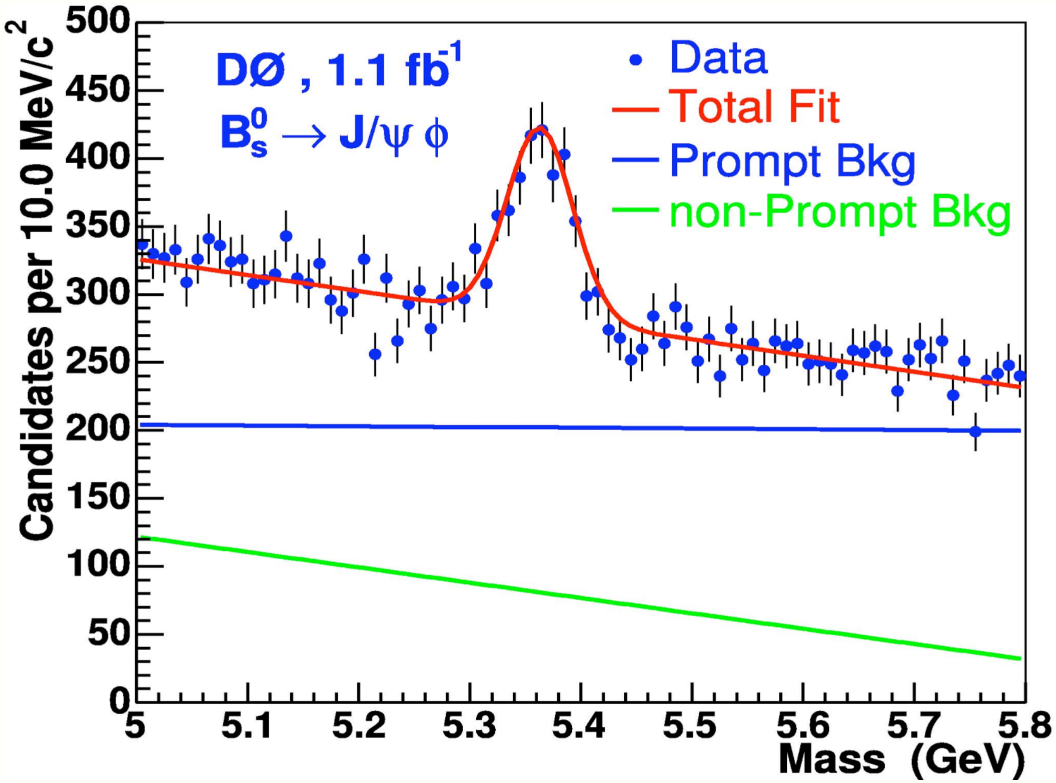
Even and odd paths distinguishable with angular analysis of final state particles

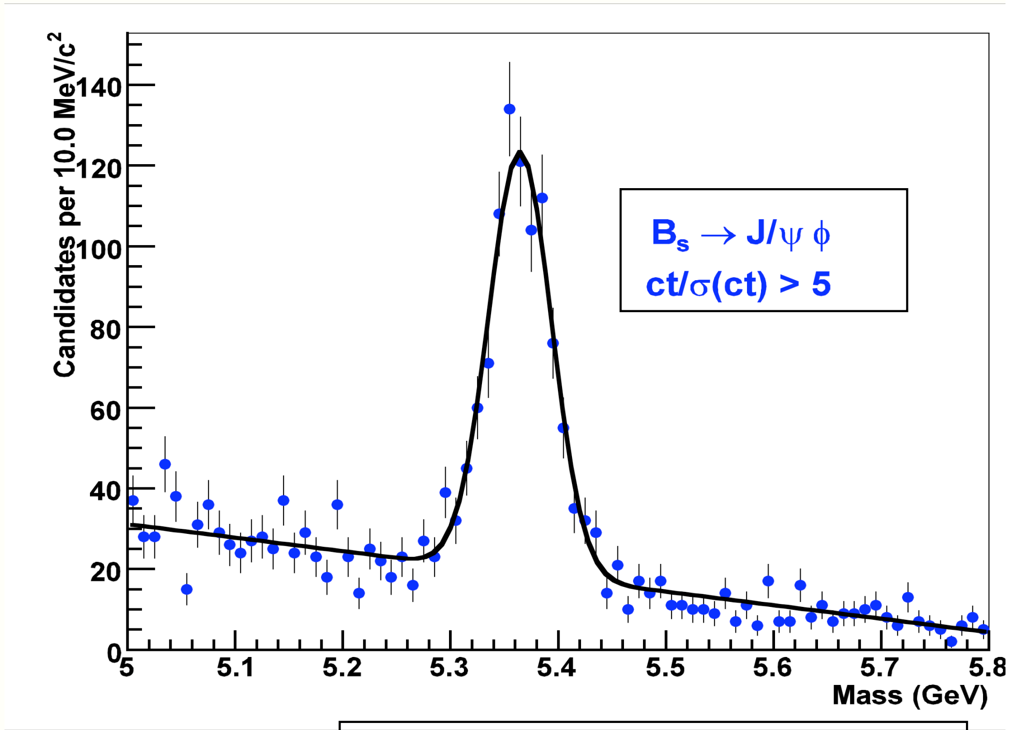
$A_0 \ A_{||}$ $\qquad$ $A_\perp$

Even waves $\qquad$ Odd waves



$B_s \to J/\psi\ \phi$





Flight length significance > 5

1039±45 B_s Candidates